Arctic water source dynamics, stream habitat and biodiversity in a changing climate: a field-based investigation in Swedish Lappland

by

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Abstract

The dynamic interaction between different water sources plays a key role in the structure and functioning of Arctic stream systems. Ice melt, snowmelt, groundwater and rainfall mix to produce a diverse range of physicochemical conditions. The heterogeneous habitat matrix created is home to a variety of cold stenothermic species. Recent trends in earth surface temperatures associated with global warming have co-in sided with a reduction in global glacier mass balance and a hastening in the onset of spring thaw.

This field based study investigated the physicochemical habitat diversity within a glacierized Arctic catchment, Kårsavagge in Northern Sweden. Hydrological, meteorological and physicochemical data spanning 2007 to 2010 were collected with intensive collection during the summer melt seasons of 2008 and 2009. In conjunction with these data, macroinvertebrate and fish sampling was carried out during both of the intensive summer monitoring periods. The key focus of the sampling regime was to compare lateral and longitudinal habitat variability, investigate the extent to which this was linked to dynamic water source interactions by modeling contributions from identified sources and assess the impact of this physicochemical habitat template on the macroinvertebrate and fish communities in the light of predicted climate change.

The key findings discussed within are (1) Lateral habitat and biological diversity was equivalent to that observed longitudinally. (2) The ARISE framework used for modeling different water source contributions is applicable to an Arctic scenario, however its utility decreases with increasing catchment size. (3) The key habitat variables structuring macroinvertebrate and fish distribution were concerned with mediating/ mitigating the extent of the glacial signal. A conceptual model is presented that illustrates the potential impact of loss of this glacial signal on local biodiversity.

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Abbreviations

AASER	Arctic and Alpine Stream Ecosystem Research
AD	Anno Domini
ACIA	Arctic Climate Impact Assessment
ANS Station	Abisko Naturvetenskapliga Station (Abisko Scientific Research
ARISE	Alpine RIver and Stream Ecosystem
a.s.l.	Above sea level
AWS	Automatic weather station
BP	Before Present
CCF	Cross Correlation coeFficient
CPOM	Coarse Particulate Organic Matter
DD	Degree Day
DOC	Dissolved Organic Carbon
DON	Dissolved Organic Nitrogen
DIN	Dissolved Inorganic Nitrogen
EC	Electrical Conductivity
EMMA	End-Member Mixing Analysis
EPT	Ephemeroptera, Plecoptera and Trichoptera
FL	Fork Length
GMWL	Global Meteoric Water Line
HDPE	High-Density Polyethylene
IDH	Intermediate Disturbance Hypothesis
IPCC	International Panel on Climate Change
NAO	North Atlantic Oscillation

NEI	Net Energy Intake
NMDS	Non-metric Multi Dimensional Scaling
ORP	Oxidation-Reduction Potential
PCA	Principal Components Analysis
PMP	Pressure Melting Point
POM	Particulate Organic Matter
RDA	Redundancy Analysis
SRP	Soluble Reactive Phosphorus
TDS	Total Dissolved Solids
VSMOW	Vienna Standard Mean Ocean Water

Chapter 1 - Introduction and Aims

The traditional Alpine stream classification system proposed by Ward (1994) focuses on the annually dominant water sources and identifies three types of Alpine stream, defined to a large extent by temperature. Ward (1994) acknowledged that his classification system was based on a limited number of investigations and although useful and much cited e.g. (e.g. Milner and Petts, 1994; Lods-Crozet *et al.*, 2001a; Burgherr *et al.*, 2001) it is overly reliant on temperature and initial source to differentiate biotopes (Brown *et al.*, 2003; Hannah *et al.*, 2007). A spatial component is included in the form of longitudinal transition but the extent of natural spatial and temporal heterogeneity is not adequately represented.

Brown *et al.*, (2003) proposed a novel classification, ARISE (Alpine RIver and Stream Ecosystem), based upon determined proportions (% contributions) from different water sources (i.e. glaciers, snow and groundwater) rather than assigning streams to traditional ecological classes (e.g. kryal, rhithral and krenal). This approach emphasises the dynamic nature of water source contributions which vary spatially and temporally over diurnal and seasonal timescales (Brown *et al.*, 2003; 2009). This conceptual model was implemented in the French Pyrénées (Brown *et al.*, 2006d). Identification of different flow paths enabled the spatial and temporal shifts in source contributions to be elucidated. These shifts in water source corresponded to physicochemical changes that were reflected in distribution of macroinvertebrates.

Northern progression of range boundaries for some northern hemisphere species has already been observed (Warren *et al.*, 2001; Walther *et al.*, 2002; Parmesan and Yohe, 2003; Hickling

et al., 2006) and this, combined with shrinking habitat envelopes is putting stress on Arctic communities. The reason for monitoring high latitude communities with respect to climate change is twofold. Firstly, the rate of change at high latitudes necessitates a rapid assessment of how communities in these environments are structured and the identification of key parameters relating to their function. This will allow more informed assessments of the capacity of high latitude communities to react to predicted changes in climate and any associated shifts in seasonality/ ecological pressures'. Secondly, these remote areas allow us to track the signal of global warming with less interference from other anthropogenic forcing factors such habitat loss.

The aims of this project are to build upon the alternative classification system put forward by researchers at the University of Birmingham and extend it to an Arctic context (Brown *et al.*, 2003; Hannah *et al.*, 2007). Identification and appropriate classification of Arctic streams is fundamental to understanding and predicting responses to climate change but is only useful when related to the biotic communities which these responses will impact. In order to achieve this aim the following objectives were identified.

Objective 1 - Apply and evaluate the ARISE classification system longitudinally and laterally within the Kårsavagge system.

Objective 2 - Investigate the physicochemical habitat variability longitudinally and laterally within the basin and identify the key drivers of this variability.

Objective 3 – Investigate variability within the biotic component of the Kårsavagge system by relating the distribution of macroinvertebrate and fish taxa to physicochemical habitat template.

Objective 4 – Assess the potential trajectory of the Kårsavagge system in the light of predicted climate change.

Chapter 2 - Literature Review

2.1 Climate Change

Anthropogenic impact on the world since the Industrial Revolution has been so great that we may in the midst of the dawning of a new era (Crutzen, 2002; Zalasiewicz *et al.*, 2008; Zalasiewicz *et al.*, 2010). Whether or not the Anthropocene (Crutzen, 2002) becomes an accepted epoch of geologic time, it is clear that human influence on the structure and functioning of natural global systems has been extensive. One of the most pressing anthropogenic influences is that of climate change. Evidence of global warming is manifold (e.g. ACIA, 2004; Overland, 2006; Turner *et al.*, 2007; IPCC, 2007a; Callaghan *et al.*, 2010); average temperatures have steadily increased since 1850 with the rate of increase elevated to 0.18°C per decade since 1979 (IPCC, 2007b). This trend is predicted to continue with average global air temperatures forecast to rise by between 1.8 - 4.0 °C by 2100 (IPCC, 2007b). These average forecasts mask significant latitudinal variation. Polar amplification is expected to result in high latitudes exceeding global average warming (Holland and Bitz, 2003; Mcguire *et al.*, 2006; Serreze and Francis, 2006) with Arctic surface temperatures at 2100 predicted to rise 4 -7 °C above the present (ACIA, 2004; Walsh *et al.*, 2005; Schiermeier, 2006).

The recent warming trend is associated with a reduction in the extent and thickness of Arctic sea ice (Overland, 2006), a worldwide reduction in glacier mass balance (Meier *et al.*, 2003; Dyurgerov, 2003) and a reduction in the extent of snow cover (Overland *et al.*, 2004). Zemp *et al.*, (2006) predict a warming of 3 °C would result in the loss of 80% of alpine glaciers. If

global warming proceeds as forecast over the next 100 years similar or greater reductions could be expected in other glaciated regions, including the Arctic.

Spring thaw in the Arctic is occurring earlier (Magnuson *et al.*, 2000; Stone *et al.*, 2002; ACIA, 2004), winter precipitation in many Arctic regions is increasing (Frey and Smith, 2003; Jonsson *et al.*, 2010) and there is predicted to be a steady increase in the proportion of this that falls as rain (ACIA, 2004). These shifts in atmospheric water source dynamics, combined with the noted decline in global glacier volumes (Dyurgerov, 2003; Meier *et al.*, 2003; Zemp *et al.*, 2006) have implications for both the physical and chemical conditions within arctic freshwater systems (Wrona *et al.*, 2006; Milner *et al.*, 2009). The dependence of Arctic and Alpine streams on these shifting cryospheric sources makes them ideal systems for use in monitoring the impact of global warming at local, regional and global scales (Milner *et al.*, 2001; Robinson *et al.*, 2007).

A considerable body of literature exist linking various components of the hydrosphere with the distribution, life cycle and community composition of aquatic biota (e.g. Death and Winterbourn, 1995; Biggs *et al.*, 1999; Brewin *et al.*, 2000; Bilton *et al.*, 2001; Castella *et al.*, 2001; Brittain and Milner, 2001; Arscott *et al.*, 2003; Cattaneo *et al.*, 2004; Boyero, 2005; Finn and Poff, 2005; Brown *et al.*, 2006e; Beche and Resh, 2007; Chaves *et al.*, 2008; Díaz *et al.*, 2008; Alvarez-Cabria *et al.*, 2010). However, historically these investigations have focused on North America and Europe and in comparison information relating to Arctic and sub-Arctic hydrology is relatively sparse (Wrona *et al.*, 2005; Walsh *et al.*, 2005). The knowledge gap relating to Arctic structure and function therefore needs to be filled rapidly in order to assess and predict ecosystem response to this potentially catastrophic warming (Wrona *et al.*, 2005).

2.1 Aquatic biota in the Arctic

2.1. i) **Macroinvertebrates**

Macroinvertebrates are a highly diverse group of organisms presenting biodiversity at both the species and functional level (Tachet *et al.*, 2000; Bis and Usseglio-Polatera, 2004). They are found in most freshwater environments proving a key link transferring productivity from lower trophic levels and to more economically valuable species in higher ones (e.g. salmonids). Life cycles of most lotic macroinvertebrates occur over temporal scales are that are both experimentally accessible and functionally relevant to environmental change. Stream insects often need to utilize different habitat patches in order to complete development, for example the stream channel, the hyporheic zone and adjoining terrestrial regions (Danks *et al.*, 1994; Füreder *et al.*, 2005). This multi-habitat dependency makes invertebrates highly sensitive to environmental variation (Lods-Crozet *et al.*, 2001a), and therefore useful as 'integrative monitors' of hydrological, thermal or biotic change (Mcgregor *et al.*, 1995; Castella *et al.*, 2001). However, this sensitivity and the resultant inter annual variability of some stream communities has led some authors to questioned their worth as indicators of longer term environmental trends (Milner *et al.*, 2006).

Hieber *et al.*, (2005) describe freshwater invertebrate communities in terms of interactions between habitat filters. These filters refine the regional species pool down to those species capable of persisting under site specific conditions, the more specialized the habitat the greater the number of filters. The extreme seasonality and harsh conditions prevalent within most Alpine and Arctic streams define a narrow habitat filter (Füreder *et al.*, 2001; Milner *et al.*, 2001; Hieber *et al.*, 2005) and as a consequence there is a sharp reduction in species

richness and diversity with altitude and latitude (Stevens, 1992; Ormerod *et al.*, 1994; Lods-Crozet *et al.*, 2001b). Species able to cope with conditions imposed by Arctic and Alpine glacial streams are highly specialized, brimming with resistance and/ or resilience traits (Danks *et al.*, 1994; Snook and Milner, 2001; Füreder, 2007). Specific adaptations include melanism (Downes, 1965), diapause (Økland, 1991), freeze avoidance (Irons et al., 1993), freeze resistance (Bouchard *et al.*, 2006), freeze tolerance (Olsson, 1981) and merovoltine life cycles (Butler, 1982). Many taxa from cold environments also display a range of phenotypic and behavioural plasticity to account for the variety of challenges posed by the environment (for thorough reviews see Downes, 1965; Lencioni, 2004; Danks, 2007). The duration and extent of the Arctic winter relative to that of Alpine systems, which have a less extreme solar regime and mostly lack extensive permafrost (Walsh *et al.*, 2005) means that the habitat filters determining Alpine and Arctic systems are subtly different.

Alpine and Arctic glacial stream ecosystems are characterized by low diversity communities structured along gradients of environmental harshness (Ward, 1994; Milner *et al.*, 2001; Jacobsen *et al.*, 2010). The downstream evolution of the main channel habitat is well documented, as atmospheric interaction, tributary and groundwater inputs, lake storage and increasing terrestrial connectivity act to ameliorate conditions (Uehlinger *et al.*, 2003; Brown *et al.*, 2006d; Cadbury *et al.*, 2008; Finn *et al.*, 2010). These changes within stream physico-chemical conditions are associated with a gradual turnover in the macrobenthic community (Milner *et al.*, 2001a; Giaslason *et al.*, 2001; Lods-Crozet *et al.*, 2001a; Milner *et al.*, 2008).

As well as the much studied longitudinal gradients often associated with riverine ecology (e.g. Vannote *et al.*, 1980; Elwood *et al.*, 1983; Caissie, 2006) several authors have highlighted the extent to which lateral gradients exist and the role they play in maintaining local and regional biodiversity (e.g. Junk *et al.*, 1989; Ward, 1989). Recently lateral connectivity within glacial river systems and its impact on macroinvertebrate diversity has received greater interest (Brunke *et al.*, 2003; Arscott *et al.*, 2005; Malard *et al.*, 2006; Hannah and Brown, 2008), with the greater habitat heterogeneity it provides elevating local biodiversity above that observed in the main channel (Arscott *et al.*, 2005; Brown, 2007).

The extreme forcing factors within Arctic and Alpine freshwater systems led to the belief that community development within them was mostly deterministic, constrained within a narrow range by the harsh environment (e.g. Ward 1994). However Flory and Milner (1999) illustrated that competitive interactions still play a role in community assembly. They found that *Diamesa alpina*/*lupus* density was reduced by the presence of *Pagastia partica* rather than an upper thermal limit. This suggests that although colonization is limited by strong environmental filters, as these ease species turnover is mediated by competition.

2.1. ii) **Arctic charr**

All cold stenothermic species are threatened by the recent and predicted temperature increases (e.g. Mcdonald *et al.*, 1994; ACIA, 2004; Callaghan *et al.*, 2004a, b, c; Harte *et al.*, 2004). As the most northerly ranging freshwater fish Arctic charr (*Salvinus alpines*), with low thermal growth optima and low resistance to higher temperatures (Baroudy and Elliott, 1994;

Lehtonen, 1998; Larsson, 2005; Elliott and Elliott, 2010) are particularly vulnerable to predicted warming.

The optimum temperature for growth of Arctic charr is around 16°C (Larsson and Berglund, 1998; Lehtonen, 1998; Larsson, 2002) with growth suppressed above 18°C (Lyytikäinen *et al.*, 2002) but charr prefer lower temperatures, between 9.2°C to 11.5°C opting to maximize growth efficiency rather than overall growth rate (Larsson, 2005; Larsson and Berglund, 2005). This behavioural adaption to low productivity habitats, along with their high tolerance for low thermal conditions has led to their predominance in many high latitude systems (Baroudy and Elliott, 1994; Klemetsen *et al.*, 2003a), often being the only fish species present (Gulseth and Nilssen, 2001). Despite this solitude a high degree of trophic, morphological and behavioural plasticity enables charr to exploit a range of different ecological niches (e.g. Fraser *et al.*, 1998; Gulseth and Nilssen, 2001; Gallagher and Dick, 2010). Some northern lakes have been reported to contain as many as four ecologically distinct and reproductively isolated charr morphotypes: small benthic, larger piscivorous, larger benthic and planktivorous (Malmquist, 1992; Jonsson and Jonsson, 2001; Arbour *et al.*, 2011).

In populations with access to the ocean, some larger morphs switch to anadromy (Radtke *et al.*, 1996). At high latitudes, the productivity of marine systems is substantially greater than that of most freshwaters; Arctic Charr morphs able to exploit this resource grow faster and attain larger sizes than residents (Radtke *et al.*, 1996; Rikardsen *et al.*, 2000; Klemetsen *et al.*, 2003a). However migratory behaviour is also prevalent within landlocked populations as fish disperse through river systems during the melt season to feed and breed in shallower, more productive areas before returning to deeper water refugia towards the end of autumn (Babaluk *et al.*, 2001; Klemetsen *et al.*, 2003b).

Fish growth is rapid until maturity at which point the high energy costs associated with spawning cause growth to slow and size to plateau (Gullestad and Klemetsen, 1997). The energetic cost of spawning in some high latitude, low productivity regions such as Svalbard restricts spawning to every second or third year (Gullestad and Klemetsen, 1997). Age and size at maturity in Charr is determined by morph type, which in turn is determined to some extent by local habitat characteristics (Gullestad and Klemetsen, 1997; Gulseth and Nilssen, 2001; Arbour *et al.*, 2011). Larger fish are more fecund than smaller ones (Power *et al.*, 2005), so in habitats with access to ample resources either locally or via migration it may be profitable to delay maturation. In sites lacking resources and with high energy costs early maturation and spawning may be favoured. However individuals in low productivity habitats that are able to switch to higher value resources (i.e. piscivory) rapidly increase in size, are able to cope with higher energy costs of that increased size and are more fecund. This is supported by the higher incidence of bimodality of size distribution with latitude (Griffiths, 1994).

Arctic charr can be relatively long lived, sometimes attaining ages in excess of 30 years, with the age of maturity differing between morphs (Jonsson *et al.*, 1988; Gullestad and Klemetsen, 1997; Jonsson and Skulason, 2000). Larger morphs tend to mature later at around 8yrs; in contrast mature individuals from dwarf populations have been reported as early as age 2 with fork lengths of as little as 7cm (Jonsson *et al.*, 1988; Klemetsen *et al.*, 2003a). Associated with this more rapid development, smaller morphs tend to die earlier (Wooton, 1985; Gulseth and Nilssen, 2001).

Not only will warmer average water temperatures reduce the charr's potential niche, but the northward range expansion of other anadromous species of salmonids will restrict charr to

less profitable habitat (Langeland *et al.*, 1991; Nakano, 1995; Larsson, 2005). In the absence of other fish species trophic polymorphism has led to several distinct sub-populations of Arctic charr, some of which appear to be genetically distinct (Skúlason *et al.*, 1996; Jonsson and Skúlason, 2000). In multi species communities Charr tend to epibenthic, out competed in littoral zones by trout (Langeland *et al.*, 1991). If restricted to this one niche across the entire range much of the present genetic and subsequent phenotypic variability within the species may be lost.

2.2 Coldwater stream habitats

Physicochemical conditions of the main channel and the wider flood plain are determined by interaction of the initial water source, which carry inherent properties with external inputs such as solar radiation/ nutrient loading (Tockner *et al.*, 1997; Malard *et al.*, 2000; Brown *et al.*, 2003). Glacial melt water for example is cold (< 2°C), nutrient poor, dilute, turbid (due to high sediment loads) and shows marked seasonal and diurnal variation in flow (Ward, 1994; Gurnell *et al.*, 2000). In contrast groundwater has a relatively constant temperature (often stated as summer cold/ winter warm), a high solute content due the rock: water ratio of the flow path, very low turbidity with no diurnal and a much less seasonal flow rate (Smith *et al.*, 2001; Brown *et al.*, 2005).

Arctic and Alpine environments are extreme both in terms of temperature and disturbance (Danks *et al.*, 1994; Hodson *et al.*, 1998; Gurnell *et al.*, 2000; Brittain and Milner, 2001; Brown *et al.*, 2003; Wrona *et al.*, 2005). Key physical habitat variables identified as important in structuring stream communities are water temperature (Ward, 1994a; Milner *et al.*, 2001b;

Friberg *et al.*, 2001; Ilg and Castella, 2006), substratum stability (Lods-Crozet *et al.*, 2001a; Robinson *et al.*, 2001; Snook and Milner, 2001c), substratum calibre (Lencioni and Rossaro, 2005; Dumnicka *et al.*, 2007), turbidity (Brown *et al.*, 2006d) and hydrochemistry (Ward, 1994; Friberg *et al.*, 2001), with percent of glaciated catchment giving a relatively crude, yet highly useful measure of overall harshness (Füreder, 2007).

The longitudinal development of glacial stream invertebrate communities has been covered extensively. Milner and Petts (1994) proposed the original conceptual model for longitudinal community development. This model combines substrate stability with specific temperature thresholds, and modifying morphology such as catchment lakes or tributary inputs. Chironomidae species dominate close to the glacier snout with Diamesa being the sole genus at temperatures below 2°C. Above 2°C other Chironomidae appear as do Simuliidae, above 4°C Plecoptera and Ephemeroptera species can colonise. This rise in water temperature occurs alongside increasing stability. The model was revised by Milner *et al.*, (2001a) to incorporate data from the Arctic and Alpine Stream Ecosystem Research (AASER) programme and has been seen to accurately approximate longitudinal species succession in glacial streams (e.g. Lods-Crozet *et al.*, 2001a; Snook and Milner, 2001; Füreder *et al.*, 2005; Füreder, 2007). This deterministic model of species succession is only reliable during summer, when physical habitat variables are extreme (Castella *et al.*, 2001; Milner *et al.*, 2001a; Saltveit *et al.*, 2001). In more benign periods, such as the Alpine winter or early spring in Arctic streams, species distribution may be determined by a more subtle suite of factors, including biotic interactions (Flory and Milner, 1999). Lateral organisation of invertebrate communities has received much less attention than the longitudinal pattern but similar factors,

along with water source and permanence are highly significant (Robinson *et al.*, 2001; Rüegg, 2004; Robinson and Matthaei, 2007).

The assertion of Milner and Petts (1994) that temperature and substrate stability are the dominant environmental factors structuring biotic communities in cold, pristine environments is widely accepted (e.g. Vannote *et al.*, 1980; Ward, 1985; Milner *et al.*, 2001a; Snook and Milner, 2001b; Lods-Crozet *et al.*, 2001a; Ilg and Castella, 2006). The impact of temperature is four fold:

i) It determines the maximum rate of metabolism (Vannote *et al.*, 1980; Ward, 1985).

ii) It subjects animals to potentially catastrophic freezing events (Danks, 2004).

iii) It plays a role in habitat stability (Oswood, 1997; Huryn *et al.*, 2005).

IV) It is one of the keys determinants of ontogenetic succession and emergence (Ward, 1994; Füreder *et al.*, 2005).

In streams where the water is likely to freeze, animals that are not freeze tolerant need either to move away from the freezing areas or migrate to habitats which are not subject to freezing (Irons *et al.*, 1993; Oswood, 1997). Refugia frequently sought include the hyporheic zone, deeper sections of water such as lakes (Irons *et al.*, 1993; Babaluk *et al.*, 2001) or groundwater sourced tributaries (Robinson *et al.*, 2001).

The propensity of semi-voltinism among Arctic and Alpine invertebrates (Snook and Milner, 2001; Füreder *et al.*, 2005) and the restricted spawning events of certain populations of Arctic charr (Gullestad and Klemetsen, 1997) are a testament to the impact of the thermal regime on production and metabolism. However not all species cope with the hostile conditions by slowing down (Danks *et al.*, 1994). Some take advantage of the so called 'hot moments', short periods in spring and autumn, when conditions become more benign, to carry out their entire life cycle (Hieber *et al.*, 2002). In certain Alpine streams with appreciable groundwater input, the most benign conditions may occur in winter (Robinson *et al.*, 2001; Burgherr and Ward, 2001; Schutz *et al.*, 2001). The cessation of glacial run-off leaves relatively constant, warm, clear water often supporting periphyton mats (Uehlinger *et al.*, 1998; Malard *et al.*, 1999; Brown *et al.*, 2005). Robinson *et al.*, (2001) suggested under these winter conditions invertebrate biomass and density may reach a maximum. Equivalent 'hot moment' utilization cannot occur during the Arctic winter due to the extreme conditions, including little or no sun for primary production (Mcbean *et al.*, 2005). Despite this, similar adaptive behavioural strategies have been observed in Arctic fauna, for example laying eggs on south facing banks to optimise conditions for larval development (Danks *et al.*, 1994).

Substrate stability has been noted as a key variable determining invertebrate distribution in several Alpine and Arctic studies (e.g. Resh *et al.*, 1988; Cobb *et al.*, 1992; Milner *et al.*, 2001a; Snook and Milner, 2001; Robinson *et al.*, 2001; Füreder, 2007; Parker and Huryn, 2006) and as the dominant physical variable by Lods-Crozet *et al.* (2001a). Substrate stability is related to disturbance regime and several authors have related community response to this variable to Connell's (1978) Intermediate Disturbance Hypothesis (IDH) (e.g. Death, 1995;

Townsend *et al.*, 1997b; Ward and Tockner, 2001). The implication being that the maximum diversity in macroinvertebrate assemblages will be found in habitats of median disturbance.

Townsend *et al.*, (1997b) cited general invertebrate traits for resilience in stream habitats (the ability to recover from to pre-disturbance levels) as: Small body size, high adult mobility and habitat generalist. Traits for resistance (capacity to withstand disturbance without appreciable loss of numbers) were: clinger, streamlined/ flattened and two or more life stages outside of the stream. Snook & Milner (2001) found that similar traits described the invertebrate community in Alpine headwaters and are more concentrated the higher altitude the reach under consideration. However Füreder (2007) highlighted differences between the traits described by Townsend *et al.*, (1997b) for lowland streams and those applicable to glacial streams. Communities from the more disturbed habitats, those close to the glacier had reduced numbers the traits 'two or more life stages outside of the stream' and 'habitat generalist'. This may relate to the harsh terrestrial environments experienced at high altitudes. It is likely that a very similar suite of traits are present in the Arctic lotic stream biota, though again they may be even more advanced (i.e. more specialised) given the faster rate of vernal temperature increase seen in some Arctic systems relative to Alpine ones (Irons and Oswood, 1992).

In contrast to the above examples Brown *et al*. (2006d) found that water quality, (e.g. suspended sediment concentration), was more important than water quantity (i.e. discharge) in determining benthic distribution. Brown *et al.*, (2006d) propose that as alpine stream invertebrates are highly adapted to disturbance other, non disturbance related environmental factors dominate. The same may well be true for fish. Despite being adapted to the extremes of Arctic environments, a high level of suspended sediment still negatively impacts

salmonids, damages gill rakers (Lake & Hinch, 1999) and impeding the success of visual predation (Berg, & Northcote, 1985; Bilotta & Brazier, 2008).

2.3 What determines the physico-chemical habitat within a stream?

The following pages describe some of the habitat characteristics present within Arctic and Alpine streams and how they impact the physico-chemical parameters of relevance to stream invertebrates and fish.

2.3. i) **Water temperature**

Water temperature is determined by the interaction of source temperature with external heating and cooling. In the absence of geothermal activity (which can be significant (e.g. Izaguirre *et al.,* 2006)) the dominant energy input comes from solar radiation, with a contribution from sensible heat transfer, friction, biological and chemical processes all mitigated by local factors (Webb and Zang, 1997; Hannah *et al.*, 2004; Caissie, 2006; Hannah *et al.,* 2007). The extent to which water temperature reflects that of its source is primarily dependant on how close to the source the temperature is measured (Caissie, 2006; Cadbury *et al.*, 2008). Macan (1958) found water temperature gradually equilibrates to air temperature as you move downstream and such longitudinal temperature gradients are an accepted feature in the headwaters of glacial streams (Milner and Petts, 1994; Ward, 1994; Lods-Crozet *et al.*, 2001a). This distance from source - temperature relationship is mediated by local morphological, ecological and hydrological factors as well as latitudinal and altitudinal ones

(Clark *et al.*, 1999; Dovara and Milner, 2000; Uehlinger *et al.*, 2003; Caissie, 2006; Brown and Hannah, 2007; Cadbury *et al.*, 2008).

Aspect plays a significant role in received insolation and thus on the extent of snow cover, timing of spring melt, water source and thermal regime (Boyer *et al.*, 2000; Beylicha *et al.*, 2004; Brown *et al.*, 2006b). In the Northern Hemisphere north facing slopes experience lower daily insolation amounting to fewer degree by days than those with a southerly aspect. Alpine and Arctic water courses flowing from sources on North facing slopes therefore experience cooler average temperatures and reduced solar heating (Brown *et al.*, 2006a). Spring melt occurs later and windows of benign conditions for biota to exploit, so called 'hot moments' (Mcclain *et al.*, 2003) are even more fleeting. Lower temperatures on these slopes reduce rates of chemical and physical weathering and as a consequence stream runoff has low concentrations of TDS and locally sourced ions (Beylicha *et al.*, 2004).

Albedo varies between water of different colour and turbidity (Oke, 1978; Cogley, 1979; Kling *et al.*, 1992). These parameters vary in Arctic and Alpine systems from tundra streams with waters coloured by leached organics or eroding peat (Harper, 1981; Kling *et al.*, 1992; Hershey *et al.*, 1997) to spring streams of high clarity (Ward, 1994) to highly turbid glacial streams replete with glacial sediments (Gurnell *et al.*, 2000). Water colour and turbidity also impact transmissivity (Irwin and Pickerill, 1982) and the depth of the photic zone (Dobson and Frid, 1998). Radiative heating of the substrate will be greatest in the least turbid and least coloured streams. In highly turbid or coloured streams, bed sediments will be heated solely from conductive transfer either from the water column or hyporheic water (Caissie, 2006). Given that turbidity changes seasonally (Irwin and Pickerill, 1982; Hodson *et al.*, 1998), and longitudinally (Dovara and Milner, 2000; Martin and Soranno, 2006); and is dependent on

upstream morphology and tributary inputs (Milner *et al.*, 2001a) a range of transmissivities are present within most coldwater stream systems.

In conjunction with radiative heating and exchange occurring at the water-air interface at the surface, bed-water column heat exchange also plays a significant role in the net energy budget (Johnson, 2004; Caissie, 2006). The extent the bed plays in absorbing and reflecting solar radiation is mediated by the transmissivity and depth of overlying water, which itself is determined by local morphology, upstream morphology and contributory water sources (Milner and Petts, 1994; Dobson and Frid, 1998; Brown *et al.*, 2006c). It has been suggested that bedrock streams have a small thermal range with reduced diurnal variation due to daytime absorbance and night-time emmitance of the bedrock (Beschta and Weatherred, 1984). However the extent to which bedrock acts as a daytime heat sink and night-time heat source is largely dependent on the physical and reflective properties of the rock type, with highly reflective rocks producing elevated daytime temperatures and acting as limited heat stores (Johnson, 2004). Where the bed material is not continuous bedrock the dominant thermal interactions are conduction and advective transfer to hyporheic poor water (Johnson, 2004; Caissie, 2006) although depending on substrate size and heterogeneity the thermal properties may also play an important role.

2.3. ii) **Bed Stability**

The threshold value for particle movement is not simply related to particle size but dependent on shape, stream bed gradient, position within the channel in relation to the flow and to other particles (Duncan *et al.*, 1999; Gordon *et al.*, 2004). The immediate environment surrounding

a particle is also relevant as it can mediate the maximum flows experienced (Gordon *et al.*, 2004); large boulders can create a 'flow shadow' within which a number of smaller particles are retained. These micro-form bed clusters (MBC) form important flow refugia during flood events (Biggs *et al.*, 1997a;b). Various measures of bed stability have been considered such as tracer stones (Death and Winterbourn, 1994; Townsend *et al.*, 1997a; Lenzi, 2004), FST-hemispheres (Statzner and Müller, 1989; Winterbottom *et al.*, 1997; Möbes-Hansen and Waringer, 1998), calculated instability indices based on hydraulic measurements (Cobb and Flannagan, 1990; Duncan *et al.*, 1999) and the bed component of the Pfankuck index (e.g. Pfankuch, 1975; Death and Winterbourn, 1994; Gíaslason *et al.*, 2000; Hieber *et al.*, 2005; Milner *et al.*, 2006b). All of these approaches carry their own positives and negatives, and tend to focus on, or neglect at least one element of bed stability. Rather than a single index, Death *et al* (1994) proposed an agglomerative stability score created by combining various individual measures. They suggested that this gives a fuller representation of the 'real' site stability and this approach has been adopted by some authors (e.g. Death, 1996; Brown *et al.*, 2006d). Recently, in a comparison of stability indices Schwendel *et al*, (2010) noted that the Pfankuck index gave the best approximation of an agglomerative stability score but cautioned against observer bias. Its effectiveness and ease of estimation has led the Pfankuck index to be the most quoted single measure of bed stability in the literature of alpine and arctic streams.

Channel stability works on several spatial and temporal scales with regards to biota (Poff and Ward, 1990; Lake, 2000; Holyoak *et al.*, 2005; Brown, 2007). In the first instance a frequently moving channel either as a whole or as part of a braided channel network (assuming that the move is caused by a high flow event) results in regular removal and redistribution of habitat patches (Townsend, 1989; Lake, 2000; Arscott *et al.*, 2002). The

frequency with which patches are created and destroyed and importantly the time in between for the patches to develop will determine what, if anything, can maintain a population at the site (Townsend, 1989; Lake, 2000; Brown, 2007). At the scale of the individual any disturbance to channel morphology that occurs with a frequency greater than a generation time is likely to result individual removal, unless that individual can mitigate the impact via differential habitat use. This may relate to utilization of in stream refugia/backwater regions (Townsend, 1989; Robertson *et al.*, 1995; Winterbottom *et al.*, 1997) or timing terrestrial life stages to coincide with the period of high flows (Brewin *et al.*, 2000).

Stability plays a secondary role in the distribution of macroinvertebrates by structuring moss distribution (Friberg *et al.*, 2001; Parker and Huryn, 2006). Recently the distribution of moss in Arctic streams has been highlighted as a habitat modifier, increasing the development of stable habitats, trapping organic particles, providing a substrate for epilithic algae and contributing to habitat complexity (Lee and Hershey, 2000; Lencioni and Rossaro, 2005; Parker and Huryn, 2006). The positive impact of moss on invertebrates appears to be most pronounced in bedrock and boulder streams where the greatest increases in habitat complexity is achieved (Lencioni and Rossaro, 2005; Parker and Huryn, 2006). It has also been suggested that not only are bryophytes found in more stable habitats but that they act to modify local habitat to increase stability (Suren *et al.*, 2000), further enhancing their positive impact on some macroinvertebrates.

2.3. iii) **Water chemistry**

Local rate of weathering and solute supply plays a large role in determining aquatic production, especially in cold, headwater streams with limited allochthonous inputs and upstream supply (Battin *et al.*, 2004; Hodson *et al.*, 2004; Quinton and Pomeroy, 2006). This impact on the rate and distribution of primary productivity is transferred up through the trophic levels to macroinvertebrates and higher organisms, some of which are of high economic relevance (Benstead *et al.*, 2005). The cold climate adds an extra facet to temperate pattern of chemical inputs as it is extremely seasonal. The snowpack acts as a reservoir for up to eight months of wet and dry deposition the majority of which is then released during the first few days of the spring melt (Cragin *et al.*, 1995; Quinton and Pomeroy, 2006).

The combination of spatially and temporally variable meltwater sources (Cragin *et al.*, 1995; Malard *et al.*, 1999) and associated hydrochemical pulses is reflected in spatially and temporally variable channel chemistry (Williams and Melack, 1991; Malard *et al.*, 1999; Beylicha *et al.*, 2004). In regions where an obvious flood plain is present valuable nutrients and DOC can be sourced for isolated pools/ channels that connect to the main system during periods of increased hydrological connectivity, for example subsurface flows stimulated by snowmelt (Malard *et al.*, 1999; Robinson and Matthaei, 2007).

Arctic and Alpine streams, like most freshwater systems are limited primarily by P concentration (Benstead *et al.*, 2005), with values of soluble reactive phosphorus (SRP), frequently below detectable limits (Hodson *et al.*, 2004; Hodson *et al.*, 2005; Izaguirre *et al.*, 2006). The main sources of P and N in glacial catchments are glacial runoff and snowmelt respectively (Tranter *et al.*, 1996; Malard *et al.*, 1999; Hodson *et al.*, 2004). Relatively high

concentrations of TP have been observed in several studies yet due to high adsorption of P onto suspended sediments very little of this is biologically available (Hodson *et al.*, 2004; Hodson *et al.*, 2005). The impact of site specific conditions is clear from the range of observed results. Along with the phosphorous, some authors have implied that both P and N are limiting (Miller *et al.*, 1986); whilst others have found that rather than nutrients it is flow velocity that limits primary production (Rinke *et al.*, 2001). In other Arctic and Alpine systems observed productivity was comparable (in terms of the invertebrate biomass), to that from terrestrial streams (Cowan and Oswood, 1984).

The main source of dissolved organic carbon (DOC) in arctic and alpine catchments is dependent on the type and position in a catchment. For example tundra streams receive organic enrichment as the seasonal deepening of the active layer exposes organic deposits to the surface hydrology, storm flows can therefore mobilise large quantities of DOC as well as dissolved inorganic nitrogen (DIN) and dissolved organic nitrogen (DON) (Maclean *et al.*, 1999). Non tundra catchments receive much reduced DOC inputs, usually associated with seasonal snowmelt remobilising surface organics during overland flow or rapid through flow remobilizing organics from the limited soil pool (Maclean *et al.*, 1999).

Apart from aeolian deposition, ions available to glacial streams are dependent on catchment specific geology, regolith and moraine deposits (Kling *et al.*, 1992; Tranter *et al.*, 1996; Campbell *et al.*, 2001; Beylicha *et al.*, 2004). Catchment age is important in hydrochemical weathering; meltwaters routed through old, thin regolith are more dilute than those routed though younger, less denuded deposits (Kling *et al.*, 1992).

2.3. iv) **Inputs and transformations**

Within a given water body physico-chemistry exhibits variation over different temporal and spatial scales (Fountain and Tangborn, 1985; Hannah and Gurnell, 1999; Gurnell *et al.*, 2000; Brown *et al.*, 2003; Macintyre *et al.*, 2006; Robinson and Matthaei, 2007). However, within any catchment there will be numerous different water bodies, the boundaries of which are often ill defined and some of which are only intermittently connected, i.e. during seasonal high flows (Junk *et al.*, 1989; Fisher *et al.*, 1998; Brown *et al.*, 2003; Malard *et al.*, 2006; Gray and Harding, 2007; Robinson and Matthaei, 2007). Physico-chemistry throughout the catchment is therefore not only a function of within system transformation but also on exchange and interaction between different water bodies (Brown *et al.*, 2003).

If a lake is regarded as a serial discontinuity in the flow (Ward and Stanford, 1983; Kling *et al.*, 2000; Arp *et al.*, 2007) which alters downstream lotic conditions (Milner and Petts, 1994; Milner *et al.*, 2001b), its impact is dependent on specific limnological parameters. The predicted renewal time of Toolik Lake, Alaska is 0.5 years but water from the predominant inflow has a winter transit time of five days (O'brien *et al.*, 1997). As this stream is also the dominant source of nutrients its rapid through-flow and presumed limited mixing has been postulated as the cause Toolik Lakes' extreme oligotrophic status (O'brien *et al.*, 1997). Given the limited interaction of lake and stream water it does not seem unreasonable to assume that a similar lack of physico-chemical coupling exists between the main body of water and at least a proportion of the outflow.

In arctic and alpine systems where significant interaction between bulk lake water and inflow occurs, subsequent outflow's are generally assumed to represent a transition to more benign

conditions (Brittain and Milner, 2001; Milner *et al.*, 2001a; Caissie, 2006; Arp *et al.*, 2007). Lakes have been seen to attenuate harsh thermal and stability conditions, and alter downstream water chemistry on several occasions (Brittain *et al.*, 2001; Maiolini and Lencioni, 2001) however this ameliorating effect is not guaranteed. Early season snowmelt which is relatively warm, can pass rapidly over colder lake water with limited mixing (Wrona *et al.*, 2005). In instances such as this where inflows are warmer than lake waters the outflow could reset longitudinal succession, acting like a glacial tributary (Milner *et al.*, 2001a), especially if lake bathymetry or wind produces significant vertical or lateral mixing (Irwin and Pickerill, 1982; Dobson and Frid, 1998). Residence time plays an important role in lake impact on the longitudinal physico-chemical profile, with longer flushing rates increasing the time for lacustrine biogeochemical processing and enhancing the possibility of thermal transfer or chemical exchange (Kling *et al.*, 2000). It must be recognized that a temporal component is also at work regarding lake impact (Arp *et al.*, 2006) and this will often be a feedback relating to seasonal patterns within inflows. A lake with a larger volume, created by higher inputs has an increased impact on the longitudinal physico-chemical profile (Arp *et al.*, 2006).

It must be remembered that Inlet-outlet differences are not necessarily due solely to within lake transformations (Kling *et al.*, 2000). Beylicha *et al.* (2004) found the increase in solute concentration of the outflow relative to the inflow in a Swedish Lake, Latnjajaure, was due to solute input from the lake catchment.

2.3. v) **Bed sediment**

Bed sediment type and heterogeneity determines the extent of hyporheic zone –channel water interaction and hydrologic resident time (Boulton *et al.*, 1998; Malcolm *et al.*, 2004; Pretty *et al.*, 2006). In regions of high potential hyporheic exchange, large loads of fine sediment can impede sediment porosity, by clogging interstices (Boulton *et al.*, 1998). Glacial runoff can carry extremely high fine sediment loads (glacial flour/ Milk) (Gurnell *et al.*, 2000; Lods-Crozet *et al.*, 2001a) so hyporheic exchange can be restricted in streams with high glacial influence. However, as turbidity displays seasonal and diurnal patterns (Brown *et al.*, 2003), windows of stream clarity following sediment flushing (e.g. from snowmelt) may reconnect the hyporheic zone with the water column and play a role in producing 'hot moments' as suggested McClain (2003).

Hyporheic exchange is increased at high stream velocities and gradients which increase the hydraulic gradient between the water column and sediment water (Clark *et al.*, 1999; Pretty *et al.*, 2006) and is dependent on reach and catchment geology (Boulton *et al.*, 1998). This is illustrated in the Val Roseg an Alpine valley in the Swiss Alps, there was a longitudinal transition from a zone of net down welling at the head of the valley to a zone of net upwelling as gradient decreases and the stream and is forced into a bedrock confined canyon reach (Ward *et al.*, 1999; Malard *et al.*, 1999).

An active hyporheic zone increases reach hydraulic residence, slowing the longitudinal transmission of both flow and material (Johnson, 2004). The incorporation of upwelling and down welling within a reach, effectively high resolution eco-tones (Boulton *et al.*, 1998), often associated with riffle pool morphology (Clark *et al.*, 1999) though also affected by local

substratum (Pretty *et al.*, 2006), adds to vertical and lateral stream bed habitat heterogeneity as well as increasing spatial diversity within the entire catchment (Boulton *et al.*, 1998; Ward *et al.*, 1999; Brown *et al.*, 2007). Water flowing through the hyporheic zone incorporates a variety of flow paths, including dead zones (Boulton *et al.*, 1998). This produces a variety of microhabitats and microgradients allowing biologically mediated transformations to take place. In regions of upwelling the products of this microbial activity are released into the water column (Boulton *et al.*, 1998; Mcclain *et al.*, 2003). Upwelling zones often correspond to regions of high productivity in temperate streams (Pretty *et al.*, 2006). Productivity in Arctic and Alpine streams, which ordinarily have very limited nutrient inputs (Harper, 1981; Ward, 1994) can be elevated where warmer, more concentrated groundwater up wells (Boulton *et al.*, 1998). Large bed sediments have high hydraulic connectivity but low retention times relative to smaller ones (Pretty *et al.*, 2006). The combination of large calibre moraine and high suspended sediment may be an important factor in Arctic glacial streams, as high residence time caused by interstitial clogging can lead to anaerobic hyporheic conditions (Pretty *et al.*, 2006) shown to be damaging to fauna, especially salmonids (Malcolm *et al.*, 2003).

Many other interactions between water bodies can be seen as variations on tributary input, as even the impact of groundwater upwelling into a stream or in fact the converse is dependent on relative volumes, flow rate and of course the difference in temperature regime. The impact of tributary inputs on main channel conditions in glacial streams was highlighted by Milner and Petts (1994) and Milner *et al.*(2001b). In contrasting Norwegian rivers Brittain *et al.* (2001) demonstrated that Glacial tributaries, reset main channel conditions, extending the

dominance of the Kryal community, but nonglacial tributaries hastened transition to richer, less specialised macroinvertabrate community.

Habitat physico chemistry and stability are dependant therefore not only on the water body with its generic properties or local climatic conditions but also on the different routes the water has taken to get there. Physico chemical regime at any given point is an agglomeration of all the various flow paths, with given consideration to the relative proportion of water they each contribute, mediated and tempered by local climate and morphological conditions.

2.4 Water source

A glaciered catchment presents a unique set of challenges to hydrologists wishing to identify the dominant processes governing its hydrochemical regime. Significant contributions to proglacial stream discharge can be made by some or all of seasonal snowmelt, glacier melt, groundwater and rainfall depending on the latitude, altitude, local climatic envelope and extent of basin glacierisation (Malard *et al.*, 1999; Smith *et al.*, 2001; Brown *et al.*, 2003; Hannah *et al.*, 2005; Hodgkins *et al.*, 2009). The relative proportions of these sources that make up bulk stream flow and more importantly the speed and route by which they are transmitted to the main channel, determines in stream physico-chemical conditions (Brown, 2002; Brown *et al.*, 2006a; Cadbury *et al.*, 2008) and this has implications for aquatic biota (Friberg *et al.*, 2001; Burgherr *et al.*, 2002; Brown *et al.*, 2006d).

The classic annual hydrograph in glacial streams moves from very high discharges associated with spring snowmelt to flows consisting primarily of ice melt through summer, which

recharges groundwater supplies that continue to provide flows later in the melt season (Smith *et al.*, 2001). Overlaid on top of this seasonal pattern are deil fluctuations in discharge associated with fluctuations in received solar radiation (Ward, 1994a; Hannah and Gurnell, 2001; Füreder *et al.*, 2001) which also leads to diel water temperature variability (Brown *et al.*, 2006c). The Diurnal flow regime, intense snowmelt flows and often rapid transport of rainfall into the main channel (ACIA, 2004) create a low stability environment, with a high incidence of bed movement (Milner *et al.*, 2001b; Parker and Huryn, 2006).

Traditionally Alpine/non-tundra cold water streams and their biota are classified as kryal (glacial dominated), rhithral (snowmelt dominated) or krenal (groundwater dominated) based largely on water temperature differences (Ward, 1994; Brown *et al.*, 2003). Cold water streams are highly dynamic systems, changing as water source dominance shifts seasonally from spring (snow melt) to summer (ice-melt) through to autumn/winter (ground water) and spatially (e.g. downstream, vertically and laterally) (Malard *et al.*, 2000; Smith *et al.*, 2001). These shifts correspond to changes in solute concentration, discharge, flow regime and sediment stability yet the traditional classification system overlooks non-thermal variations in habitat quality (Brown *et al.*, 2003). It may therefore miss much of this dynamic variation and under-represent the spatial and temporal dynamics inherent within cold water systems.

Alpine streams tend to be high gradient and well mixed (Ward, 1994) and the same is true of some Arctic streams (Milner *et al.*, 1997; Friberg *et al.*, 2001; Parker and Huryn, 2006). However the dominant factors influencing cryospheric extent are different in Alpine regions compared to the Arctic. Both are impacted by the interaction of latitude and altitude (Viviroli and Weingartner, 2004; Walsh *et al.*, 2005) but of these altitude dominates alpine environments. Viviroli & Wiengarter (2004) suggested that delineating the extent of the Alps

in Switzerland by the influence of snow and glacier runoff on hydrology would yield basins of 1550m a.s.l. or more. As alpine glaciers and permanent snow fields form the source of many rivers, their influence on water supply extends to the sea, but in terms of seasonality and physico-chemistry the main influence is at high altitude (Ward, 1994; Viviroli and Weingartner, 2004). In contrast cryospheric runoff dominates Arctic hydrology down to sea level (Walsh *et al.*, 2005) and this, combined with a history of extensive glaciations (Mcbean *et al.*, 2005) means that in some instances alpine type physico-chemistry and seasonality is experienced in low altitude, low gradient streams. This departure from Ward's (1994a) alpine typology implies that his assumptions of high oxygen, fully mixed streams may not hold in some glacial arctic streams.

2.4. i) **Snowmelt (Rhithral)**

Seasonal snowmelt is the main water source for the majority of Arctic freshwater systems (Wrona *et al.*, 2005). It dominates discharge from May to late June depending on latitude and altitude (Alexander and Gu, 1997; Smith *et al.*, 2001; Wrona *et al.*, 2005; Walsh *et al.*, 2005) with some systems releasing upwards of eight months precipitation in as little as two weeks (Mcnamara *et al.*, 1998). As summer progresses the seasonal snowpack is exhausted, flows reduce and may falter (Smith *et al.*, 2001; Brown *et al.*, 2006d). Streams dependant solely on snowmelt can dry up late in mid to summer exposing resident biota to seasonal drying as well as high thermal variation (Robinson and Matthaei, 2007). McNamara *et al.*, (1998) found that snowmelt accounted for 80% of annual runoff in the Kuparuk river, Alaska in one year. However they also found high inter annual variability with snowmelt as proportion of annual runoff ranging from 52-80%.

The two key phases for solute supply to rhithral streams are the initial ion pulse and the washout and remobilisation of soil bound mineral ions and organics during subsurface flow (Walsh *et al.*, 2005; Wrona *et al.*, 2005; Quinton and Pomeroy, 2006). Early melt is very concentrated with respect to whole snow pack due to preferential elution of ions (Cragin *et al.*, 1995). The initial 30% of snowmelt runoff can contain between 50-80% of the total snow pack solutes (Cragin *et al.*, 1995). This preferential elution of nitrate and sulphate ions has been seen to cause an acid pulse in some regions (Cragin *et al.*, 1995; Tranter, 1996; Walsh *et al.*, 2005).

2.4. ii) **Glacial melt (Kryal)**

Glacial melt water is extremely cold; generally no more than 2°C close to the glacier snout (Ward, 1994a). Thermal variation of glacial melt is much reduced relative to snowmelt as both the sub and supra-glacial flow paths are thermally buffered. Sub glacial flows remain cold as radiative forcing is limited by the surrounding glacier and energy transfers to the ice walls of channels dissipate heat and add cold meltwater (Isenko *et al.*, 2005). Supra glacial flows are buffered by the body of ice over which they flow (Isenko *et al.*, 2005). Once in a proglacial stream temperatures increase with distance from the source (Smith *et al.*, 2001; Uehlinger *et al.*, 2003; Cadbury *et al.*, 2008). As with snow melt, diurnal variation has significant impact in the flow rate, with greater noon time sun associated, after a lag period, with higher flow rates (Ward, 1994; Cadbury *et al.*, 2008; Brown and Hannah, 2008). This diurnal flow pattern has implications for water temperature. The higher volume of water generated by the daily max insolation is associated with a reduction in stream temperatures due to the influx of cold water and an increased thermal capacity (Cadbury *et al.*, 2008). The

high sediment load of many proglacial streams (Gurnell *et al.*, 2000) also affects the extent of solar heating though varying transmissivity and albedo (Oke, 1978).

Timing of glacial melt is dependant, like snowmelt on specific altitude and latitude. It commences some time after initial snowmelt, and its initiation corresponds to a reduction in nitrate concentration in surface waters (Smith *et al.*, 2001; Malard *et al.*, 1999). The solute load of glacial meltwater comes either from chemical weathering of the local rock/ moraine/ sediments or the atmosphere (sea salt, nitrates, suphates, carbon dioxide and oxygen) (Tranter *et al.*, 1996; Hodson *et al.*, 2004). The water to rock ratio is the key factor determining the solute concentration and the degree of water to rock contact is dependent on the water routing. Meltwater transported through englacial or supra glacial ice channels has limited contact time with rock so is dilute relative to distributed glacial meltwater flowing along the glacier bed, exposed to high sediment loads (Tranter *et al.*, 1996; Hodson *et al.*, 2004; Martin and Soranno, 2006).

The extent to which different flow routes dominate glacial melt is dependent on i) type of glacier and ii) seasonal channel development (Tranter *et al.*, 1996). The three types of glacier (alpine, sub-polar and polar) have different channel routing patterns. Ice at the base of an alpine (warm based) glacier is as the pressure melting point (PMP). In snow covered regions this melt flows within an inefficient distributed drainage system which provides the 'delayed flow' component of melt. Over the ablation season, the snow free region of the glacier increases and underneath it develops a more channelized system which expands at the expense of the distributed system. This channelized system provides the 'quick-flow' (Tranter *et al.*, 1996).

Glacial meltwater has high and often unpredictable sediment loads, sometimes exceeding 2000 g l^{-1} (Gurnell, 1987). High sediment loads scour surfaces, backscatter light and damage fine structures of stream dwelling organisms (Oke, 1978; Lake and Hinch, 1999). Rempel *et al.* (2000) suggested that high turbidity and sedimentation in the Fraser River limited algal and grazer production.

2.4. iii) **Groundwater (krenal)**

Water which percolates down to enter the stream via deep groundwater flow or through flow undergoes ionic enrichment and exchange (Brown, 2002) and various thermal interactions (Brown *et al.*, 2003). Physicochemical transformation occurs to such an extent that slow routed water, both gradually seeping through the bed or entering via localised upwelling is recognised as separate from the original source (Brown *et al.*, 2006d). The relative proportion of this fast and slow routed water has a marked impact on stream physicochemistry and benthic community (Robinson *et al.*, 2001; Brown *et al.*, 2005; Hieber *et al.*, 2005; Robinson and Matthaei, 2007)

Spring streams fed solely by groundwater tend to approximate to the local annual air temperature and are often quoted as being 'summer cold, winter warm' (Ward, 1994) as groundwater displays much reduced seasonal and diurnal temperature variation (Tockner *et al.*, 1997; Brown *et al.*, 2003; Brown *et al.*, 2006a; Brown *et al.*, 2006c). However some groundwater flow paths transmit melt water rapidly, for example Karstic springs in the Pyrenees with deep routing retain the cold signature temperature of the meltwater sources (Brown *et al.*, 2006a). Like all flow paths groundwater is impacted by local variability and

one such key variable is aspect. Spring streams issuing from south facing slopes in the Northern Hemisphere are warmer than those flowing from North facing slopes.

2.4. iv) **Rainfall**

In the cold regions of the world precipitation occurs mostly as snow with rainfall restricted to the warmer summer months and this is increasingly true with escalating latitude and altitude. Restricted as they are, large rainfall events impact stream thermal dynamics both by increasing flow rate and reducing water column temperatures (Brown *et al.*, 2006a; Cadbury *et al.*, 2008). These episodic alterations to the seasonal runoff and thermal regime may be especially interesting in an Arctic context as the substitution of snowfall by rainfall is one of the predicted impacts of global climate change (ACIA, 2004; IPCC, 2007a).

The impact of late summer rainfall is dependent on its intensity and duration. Infiltration of low intensity rainfall may act to remobilise organics and minerals retained within the top layers of soil and reconnect, for a time the surface and ground waters (Quinton and Pomeroy, 2006). High intensity rainfall with high rates of overland flow could either add allochthonous matter from summer production or simply dilute surface water.

Chapter 3 - Study Area

3.1 Description of catchment

Kårsavagge (vagge = valley) is a steep side u-shaped valley situated in the Abisko national park, Swedish Lappland at approx 68° 20'N, 18° 20'E (Figure 3.1). It is 14km long with a roughly East-West orientation. The valley floor ranges in altitude from 1100m at its head to 630m where it drops down into the main Abisko valley at about 420m, the surrounding peaks top 1550m. The valley floor is stepped; on the highest plateau at the head of the valley sits the Kårsa glacier, a small ~1.1km^2 temperate glacier ranging in altitude from 1500-940m above sea level (a.s.l.). Meltwater from this flows down onto a second plateau. A complex system of braided channels forms at this junction as glacial melt interacts with snowmelt and hillslope groundwaters (Figure 3.2 and 3.3). The Kårsa River emerges from this braided section and flows down into the marshy, braided delta of the lower valley (Figure 3.4 and 3.5). Here the river braids again before entering Bajimus Gorsajarvi, the first of two lakes separated by a wide, shallow but still channelized section of the river.

Bajimus Gorsajavri has a maximum depth of 32m, an area of 0.95km^2, a volume of 0.018km^3 and a resident time of approximately 130 days (personal observation after much rowing) (Figure 3.6). After this lake the valley widens before the second lake. Vuolimus Gorsajavri is much shallower (personal observation) with a maximum recorded depth of only 12m (Snowball, 1991). Downstream of the lakes the Kårsa River flows down towards Abisko eventually draining into the main Abisko River.

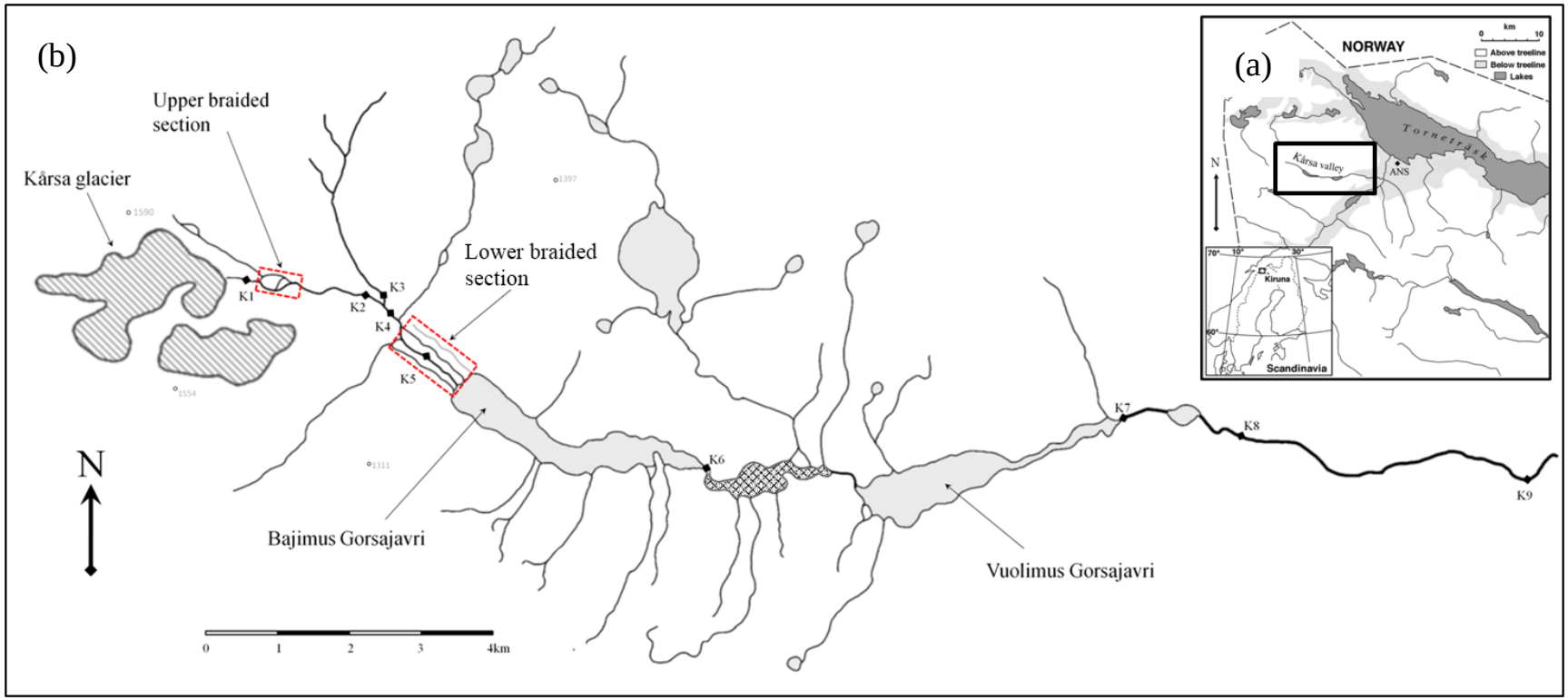

Figure 3.1 - Map of Kårsavagge. (a) Location of Kårsavagge and the Abkiso scientific research station (ANS) in Northern Sweden modified from Darmody *et al.*, (2001). (b) Detailed map of Kårsavagge showing position of longitudinal sampling sites (K1-K9), the two lakes (shaded region marks shallow transition region between lakes) and identifying upper and lower braided sections – for more detailed maps see Figure 3.2.

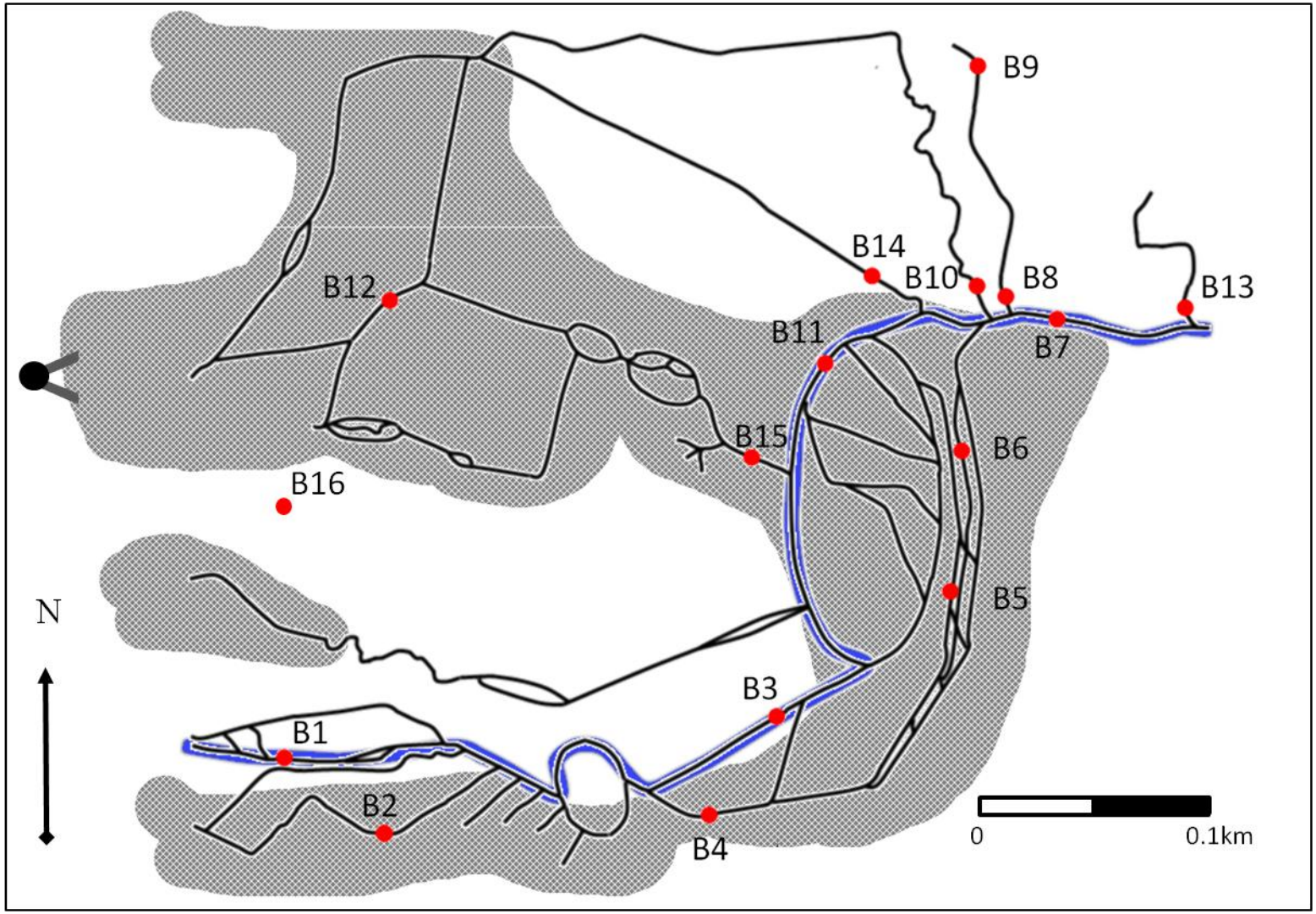

Figure 3.2 – Detailed maps of the upper braided section region of Kårsavagge. Shaded regions mark areas of highly mobile channels. Position of sampling points B1-B16. Main glaccial channel marked with thick blue line. < = Site of photographs for figure.

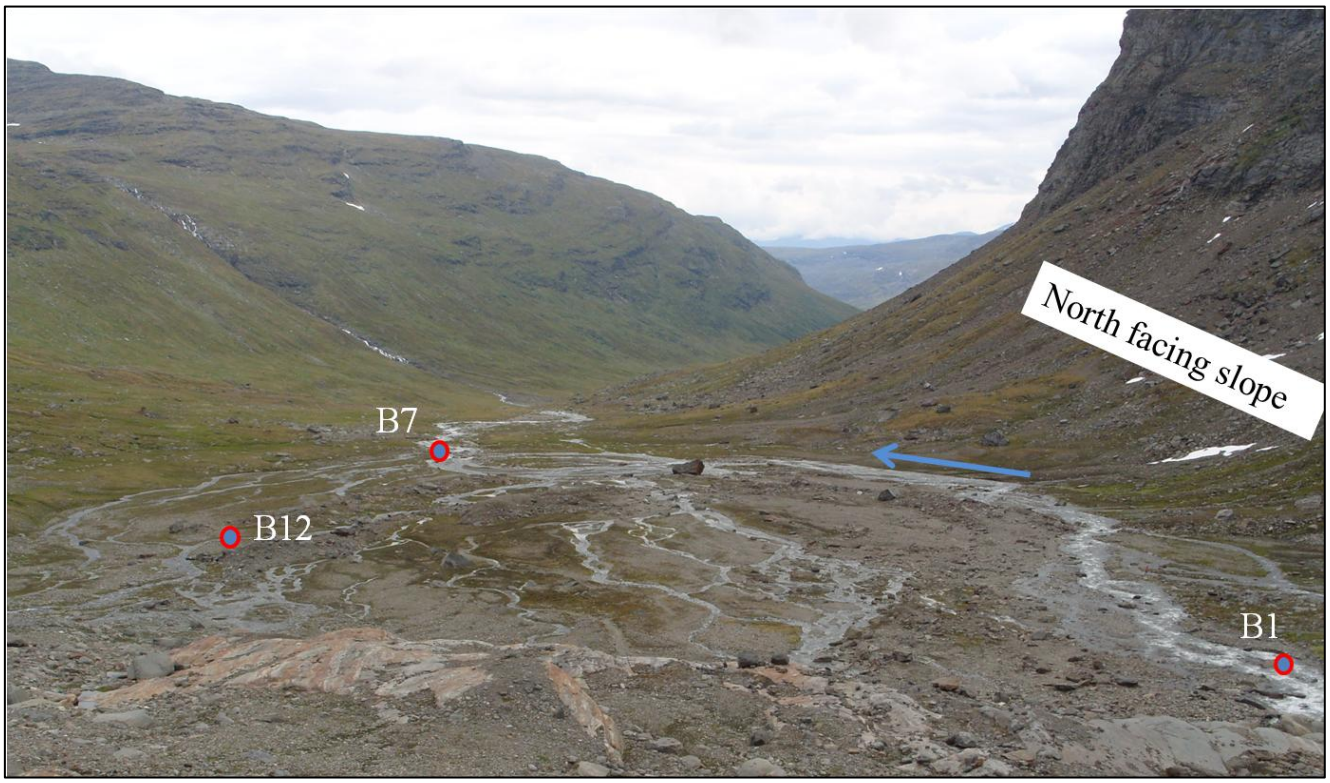

Figure 3.3 – Photograph of upper braided section showing position of B1 and B12, sites with stand alone gauging stations and B7 the site at the end of the main braids . See figure 3.2 for detailed map.
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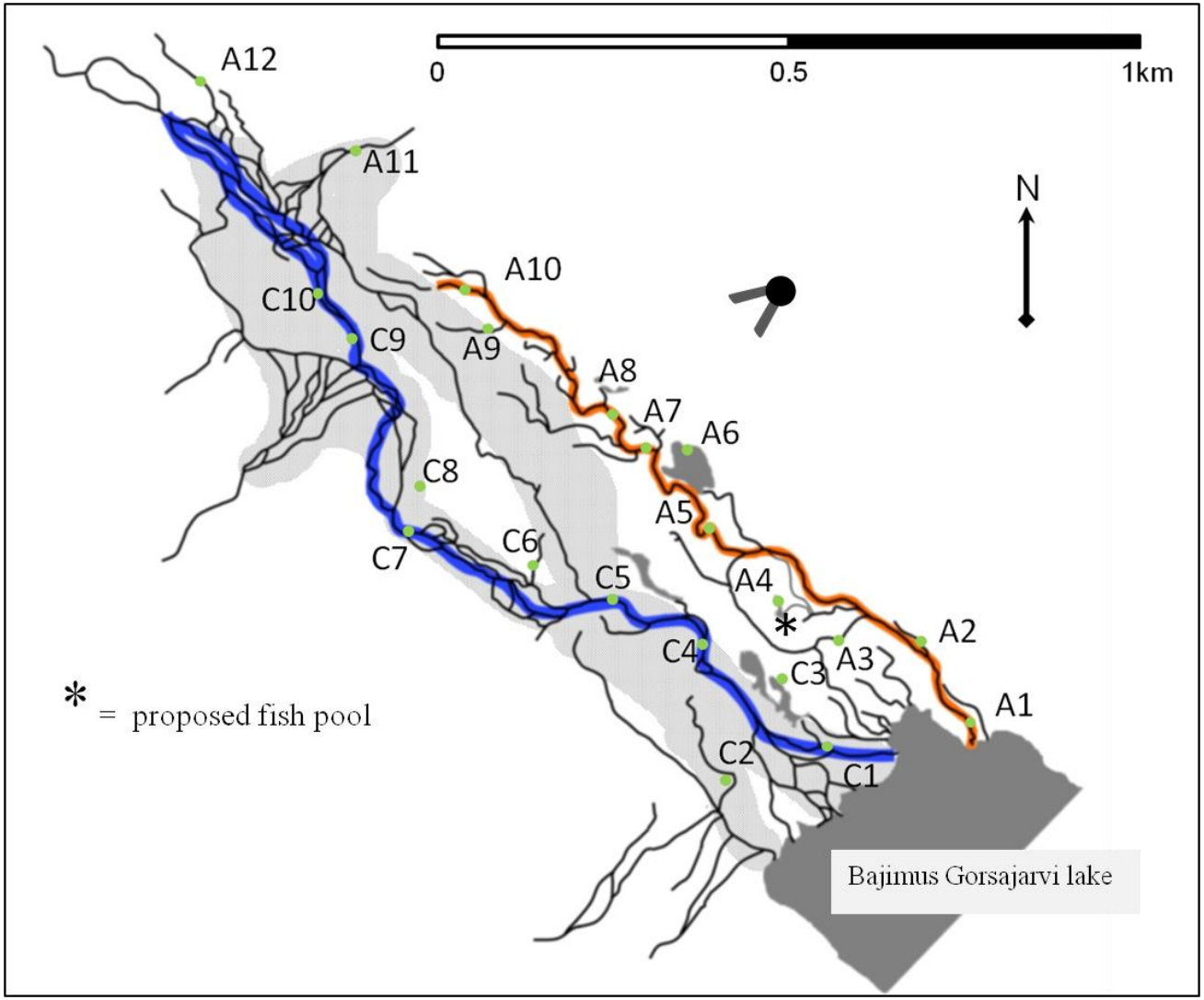

Figure 3.4 – Detailed maps of the lower braided region of Kårsavagge. Shaded regions mark areas of highly mobile channels. Position of sampling points points on the groundwater stream (A1-A10) and glacial channel (C1-C10). Main groundwater channel marked by orange line, main glacial channel marked by the blue line. **<** = Site of photographs for figure 3.5.

Figure 3.5 – Photograph of lower braided section showing position of A1 and C1, sites at the downstream end of the main groundwater stream (eastern channel) and main glacial channel respectively (western channel). Direction of arrows show the direction of flow. See figure 3.4 for detailed map.

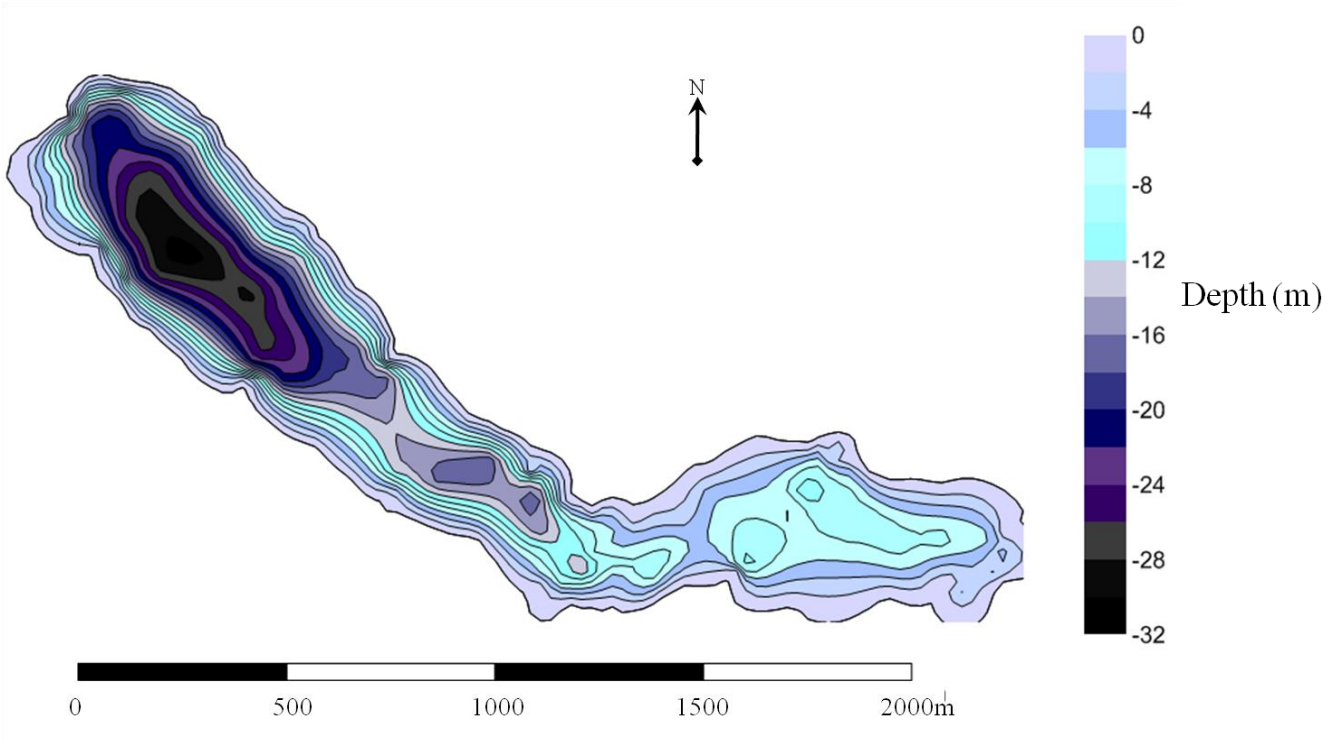

Figure 3.6 – Bathymetric map of Bajimus Gorsajarvi lake. Maximum depth is 32m in the North West region of the lake. Very approx residence time = 130 days, computed from volume ($0.018km^3$)/ discharge at outflow ($1.64m^3s^{-1}$)

Numerous tributary inputs join the Kårsa River at lower elevations. Three large snowmelt tributaries enter the delta above Bajimus Gorsajarvi Lake, two from the South facing and one from the North facing slope. There are also a small, but ecologically highly significant groundwater inputs within this region. The largest of these flows in a separate channel along the Northern side of the delta only joining the bulk melt waters within the lake. Another major input enters between the two lakes, sourced from a high altitude lake (Latrijajávri) above the south facing slopes.

3.2 Catchment geology and soils

The Abisko Mountains in which the Kårsa valley sits are part of the Caladonian range, formed over 350 million years ago by overthrusting nappes (Rapp, 1960; Lindström, 1987). The two uppermost of these allocthonous rock beds, the Köli and Seve nappes are often referred to as one complex which sit above the Abisko and Rautas nappes (Karlén, 1973; Lindström, 1987; Barnekow, 2000).

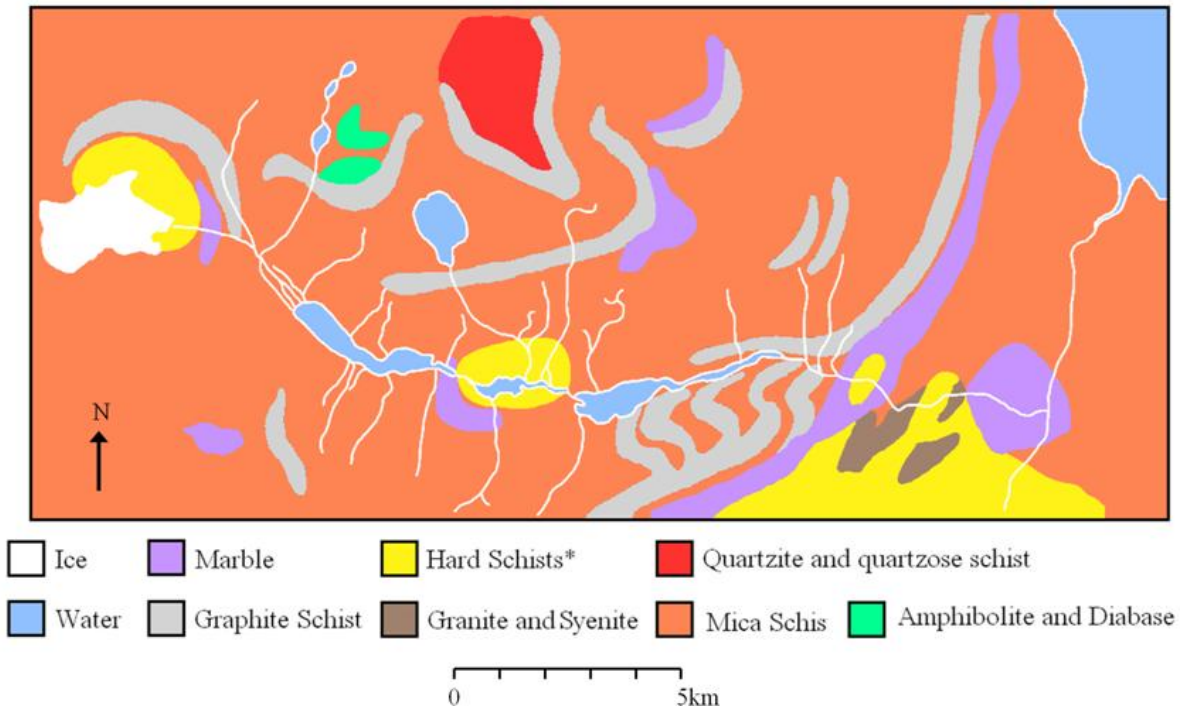

Figure 3.7 - Bedrock geology of the Kårsa valley. *quartzite, phylitic rocks and banded tectonics (adapted from Sveriges Geologiska Undersökning Ser Ba NR19, 1963 & Plant (2009)).

Schistose rocks dominate the Kårsa catchment. Resistant Mica-Schists of the Seve-Köli complex form the bulk of valley sides and floor but two windows in this upper layer, one at the head of the valley and another between the two lakes reveal outcrops of Hard Schists and dolomite of the Abisko nappe (Rapp, 1960; Snowball, 1991; Lindström, 1987) (Figure 3.7).

The surface geology of the whole region is predominately exposed bedrock overlain by a thin layer of glacial and glaciofluvial sand containing various caliber rocks (Josefsson, 1990a).

Soils are not present on the top plateau of the Kårsavagge with surfaces consisting bedrock and high caliber glacial debris. Thin soils begin to develop below 820m on the second plateau and on the south facing slopes, but remain rare on the North facing slopes until the valley opens out after Bajimus Gorsajavri. Deeper soils are found towards the Eastern end of the valley within the birch forest, but even here they are limited to ~0.45m deep.

3.3 Climate and vegetation

Northern Sweden sits along the transition Zone between Maritime Polar and Continental Polar air masses and there is a pronounced oceanic-continental gradient from west to east in the Torneträsk area reflecting this boundary (Henderson-Sellers and Robinson, 1994; Shemesh *et al.*, 2001). In years when the North Atlantic Oscillation (NAO) index is positive, maritime air masses dominates bringing warmer, wetter conditions, especially during winter which leads to greater accumulations of snow (Kohler *et al.*, 2006). When NAO is in a negative phase the Continental Polar air mass dominates bringing colder, drier conditions and increased seasonality.

The region also experiences strong seasonality due to its latitude. At of 68°21' North, Abisko sits 200km above the Arctic Circle and as such receives continual solar input between 17th June and 19th July. In winter this condition is reversed and between 18th December and 11th January the sun stays below the horizon (Andersson *et al.*, 1996).

The local climate at Abisko is also impacted by a thermal buffering effect of lake Torneträsk and the orographic effect of the surrounding highlands (Yang *et al.*, 2011). These, along with the influence of the maritime air masses give Abisko a boreal climate with temperatures 2°C higher than expected for its latitude (Wallén, 1948; Andersson *et al.*, 1996; Shemesh *et al.*, 2001; Grudd and Schneider, 1996). Annual precipitation to the West, close to the Norwegien border is around 900ml but this drops rapidly as you move further East (Callaghan *et al.*, 2010). The rain shadow cast by the High Abisko Mountains, has led to the Abisko area being referred to as one of the driest places in Sweden. An average annual precipitation of only 305ml yr^{-1} was recorded at the Abisko Scientific Research Station (ANS) between 1913 and 2008 (Yang *et al.*, 2011). This has ranged from a maximum of 475ml in 1983 to a minimum of 190ml in 1976. The majority of precipitation falls in the summer months, with July being both the warmest and the wettest (Kohler *et al.*, 2006; Yang *et al.*, 2011; Callaghan *et al.*, 2010).

The strong seasonality is reflected in the temperature regime, with average temperatures ranging from -10.8°C in January to 11.7°C in July (Yang *et al.*, 2011). Within this there is high degree of variability with winter lows dropping to -41°C and highs of 28°C recorded during summer (ANS, 2007).

The topoclimate within the Kårsavagge is a combination of large scale synoptic impacts interacting with local topography and microclimatic variations. Key to this is the valleys East-West orientation. Snow blown by the dominant Westerly's forms deep drifts and glaciers tend to be retained on the Eastern side of mountains in the lee of these prevailing winds (Holdar, 1959); hence the Kårsa glacier and its high sensitivity to climatic variations. The valley receives up to double the precipitation of the ANS (Karlén, 1979) and is cooler, with

day time temperatures in the upper valley being between 3-5°C below than those recorded at ANS (Ahlmann and Lindblad, 1940; Yang *et al.*, 2011). Air temperature within the valley is strongly influenced by glacial and foehn winds (Plant, 2009). In the lower valley Foehn winds increase temperatures during summer but towards the head of the valley temperatures are kept lower as cold air flows down off the Kårsa glacier. In combination with mountain winds, these glacial winds can cause temperatures within the valley to drop by up to 6°C (Wallén, 1948).

Table 3.1 – Dominant vegetation zones within Kårsavagge (adapted from Plant (2009)).

Altitude	Zonal description	Dominant vegetation species
>950	High alpine tundra	Sparse cryptograms mostly unvegetated
950-800	Middle alpine	Grasses and sedges; arctic bell heather (*Cassiope tetragona*), cotton grass (*Eriophorum scheuchzeri*), cushion sedges (*Carex rupestris* & *C. nardina*)
800-680	Low alpine	Cotton grass, cushion sedges, crow berry (empetrum hermaphroditum), dwarf birch (Betula nana), bilberry (*Vaccinium myrtillus)*
680-550	Dwarf shrub	Dwarf willow (*Salix herbacea*), dwarf birch, crowberry, billberry.
550<	Boreal forest	Birch (*Betula alba*) and occasional pine (*Pinus silvestris*).

Vegetation within the valley ranges from Birch forests <600m to un-vegetated ground with occasional cryptogram species towards its head. There are five main vegetation zones, each occurring at elevations 100m lower in the Kårsavagge than in the surrounding Abisko region (Table 3.1).

There are local variations in this pattern. South facing slopes have much more developed vegetation cover than North facing slopes of equivalent height on which vegetation tends to be patchy. Wet fen dominated by Carex sedges, Arctic cotton grass and sphagnum mosses cover the valley floor and delta above Bajimus Gorsajavri lake.

3.4 Current and future climate trends

There is strong evidence that recent temperature increases recorded at ANS are part of a general warming trend across the Northern Hemisphere (ACIA, 2004; IPCC, 2007a; Turner *et al.*, 2007). This warming is greater than that during the early 20th century (1930-40) warm period and, crucially, mean annual temperatures have risen above 0°C for the first time in instrumental history (Callaghan *et al.*, 2010). This is already causing range shifts and migration of ecotype boundaries (Callaghan *et al.*, 2004b; Truong *et al.*, 2006).

Warming in the late 20th century was associated with a more maritime climate with warmer, wetter winters and cooler summers (Grudd and Schneider, 1996; Jonsson *et al.*, 2010; Callaghan *et al.*, 2010). However, since the turn of the century Abisko may have entered a new climatic era with warmer wetter summers and warmer dryer winters (Callaghan *et al.*, 2010). Lake Torneträsk now freezes significantly later (30 days) and breaks up significantly earlier (17 days) than at the start of the 20thCentury (Callaghan *et al.*, 2010). Surface temperatures in Northern Scandinavia are predicted to rise by 4-5°C by 2090-99 relative to the period 1980-1999 (IPCC, 2007). If current associated trends hold, the reduced winter accumulation, later ice up and earlier spring thaw (Serreze and Francis, 2006; Callaghan *et al.*, 2010), increased intensity of extreme rainfall events (Callaghan *et al.*, 2010) and increased

frequency of winter warming (Bokhorst *et al.*, 2009) will have severe consequences for climate and vegetation patterns within the Kårsa valley.

3.4. i) **Glacial recession**

The recent glacial history of the Kårsa valley needs to be viewed in the context of longer term glacial cycles, as it was the expansion and contraction of the Northern Hemisphere ice sheets that carved the region's distinctive geomorphology (Stroeven *et al.*, 2002; Holdar, 1959). The last major glaciation, the Weichselian, started ca. 115 000 years before present (BP) and contained three periods of major glacial expansion (Lokrantz and Sohlenius, 2006).

The early Weichselian expansion, centring on Northern Sweden (115 000 to 100 000 BP) created most of Lapplands large scale glacial landforms (Hättestrand, 1998; Lundqvist, 2004; Lokrantz and Sohlenius, 2006). This warm based ice sheet had much greater erosive power than cold based glacial that came after it. During the last of these, the late Weichselian glacial (~25 000 - 15 000 BP) a sheet of ice covered Scandinavia to a depth of~2700m and extended to a latitude of 55° (Svendsen *et al.*, 2004; Lokrantz and Sohlenius, 2006). Despite its vast extent, its erosive impact in the Abisko region was relatively minor (Hättestrand, 1998; Hättestrand and Stroeven, 2002), Stroeven *et al.* (2002) estimating that it only removed about 2m from the already scoured surface (Lokrantz and Sohlenius, 2006; Hättestrand, 1998). In contrast, its recession created the characteristic glacio-fluvial landscape that now dominates (Lundqvist, 1981; Josefsson, 1990b).

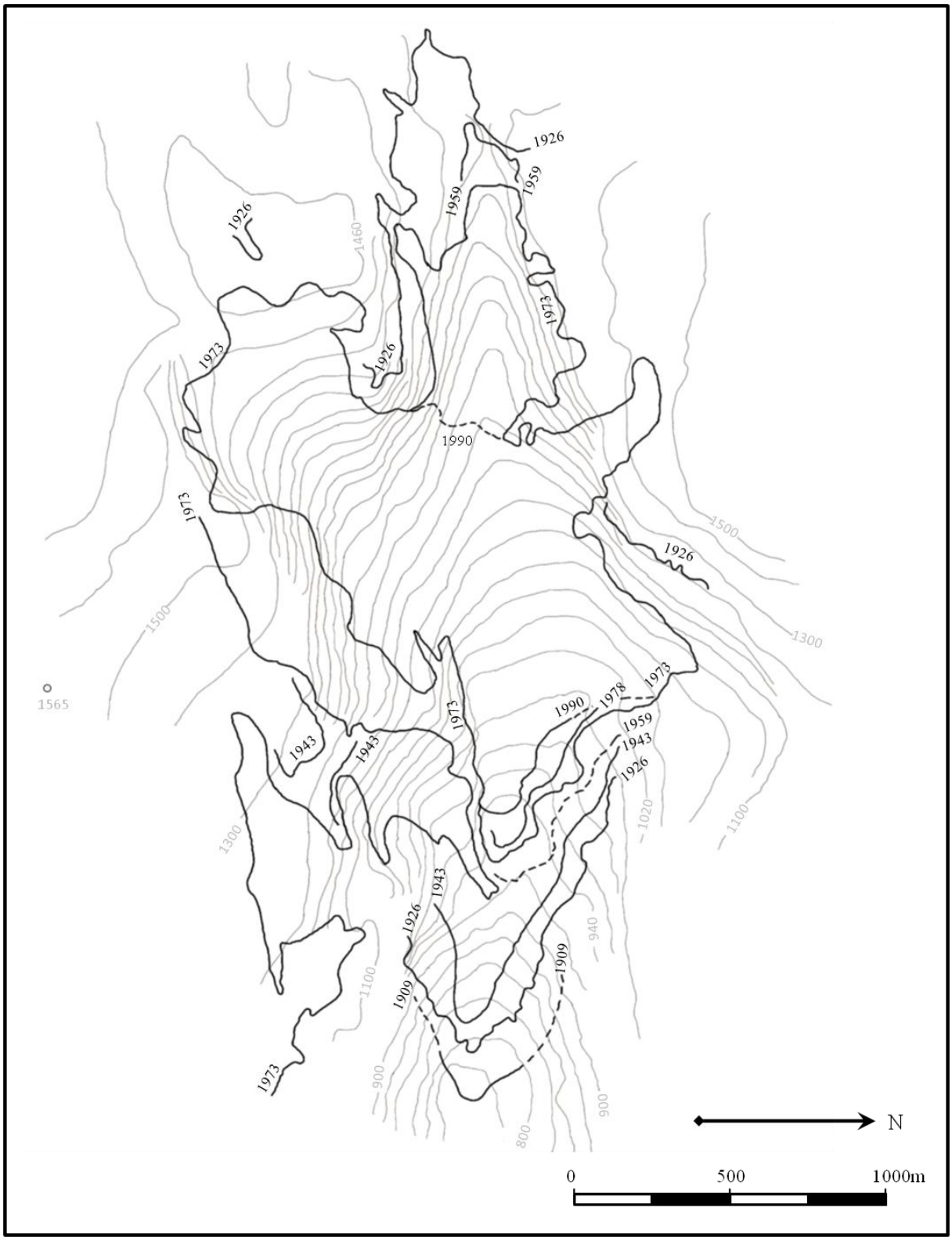

Figure 3.8 - The Kårsa glacier 1908 to 1990, adapted from Bodin (1991). Grey lines and numbers mark the contours; Black lines and dates mark extent of the body of ice during that year.

The transition from the Weichselian glacial to the Holocene interglacial ca. 11 500 BP (Lokrantz and Sohlenius, 2006) marked the end of the last glaciation, although the region around Abisko remained ice bound until at least 9 500 BP (Wallén, 1959; Karlén, 1979; Berglund *et al.*, 1996; Shemesh *et al.*, 2001; Hammarlund *et al.*, 2002; Bigler *et al.*, 2003) Various proxy measures indicate that Abisko in the early Holocene was warm, wet and maritime with temperatures estimated to be between 1.5 to 3°C warmer than present (Barnekow, 2000; Shemesh *et al.*, 2001; Hammarlund *et al.*, 2002; Bigler *et al.*, 2003). There is evidence to suggest that this climatic shift may have led to the complete disappearance of the Kårsa glacier (Ahlmann and Tryselius, 1929; Snowball, 1996; Barnekow, 1999).

Since this early Holocene warm period there has been a general cooling trend associated with a greater influence from cooler, drier continental air masses (Bigler *et al.*, 2003; Barnekow, 1999; Hammarlund *et al.*, 2002). A strong deterioration in the climate occurred around 3000-2000 BP leading to the Kårsa glacier reforming (Ahlmann and Tryselius, 1929; Berglund *et al.*, 1996; Snowball, 1996). Throughout the Holocene there have been episodic glacial expansions and contractions associated with periods of colder or warmer climate (Karlén, 1981 ; Bigler *et al.*, 2003; Karlén, 1988; Snowball and Sandgren, 1996).

The maximum extent of most Swedish glaciers probably occurred between 1700 and 1900 AD, a period known as the "little ice age" (Karlén, 1988; Hock *et al.*, 2002). During this period, average temperatures in Sweden fell ~ 1°C below current values (Hock *et al.*, 2002). The small terminal moraines in front of the Kårsa glacier are a legacy of its response to this cooling, having been dated to around two and a half centuries old (Holdar, 1959). It was towards the end of this cold period that Svenonius began documenting the marginal shifts of

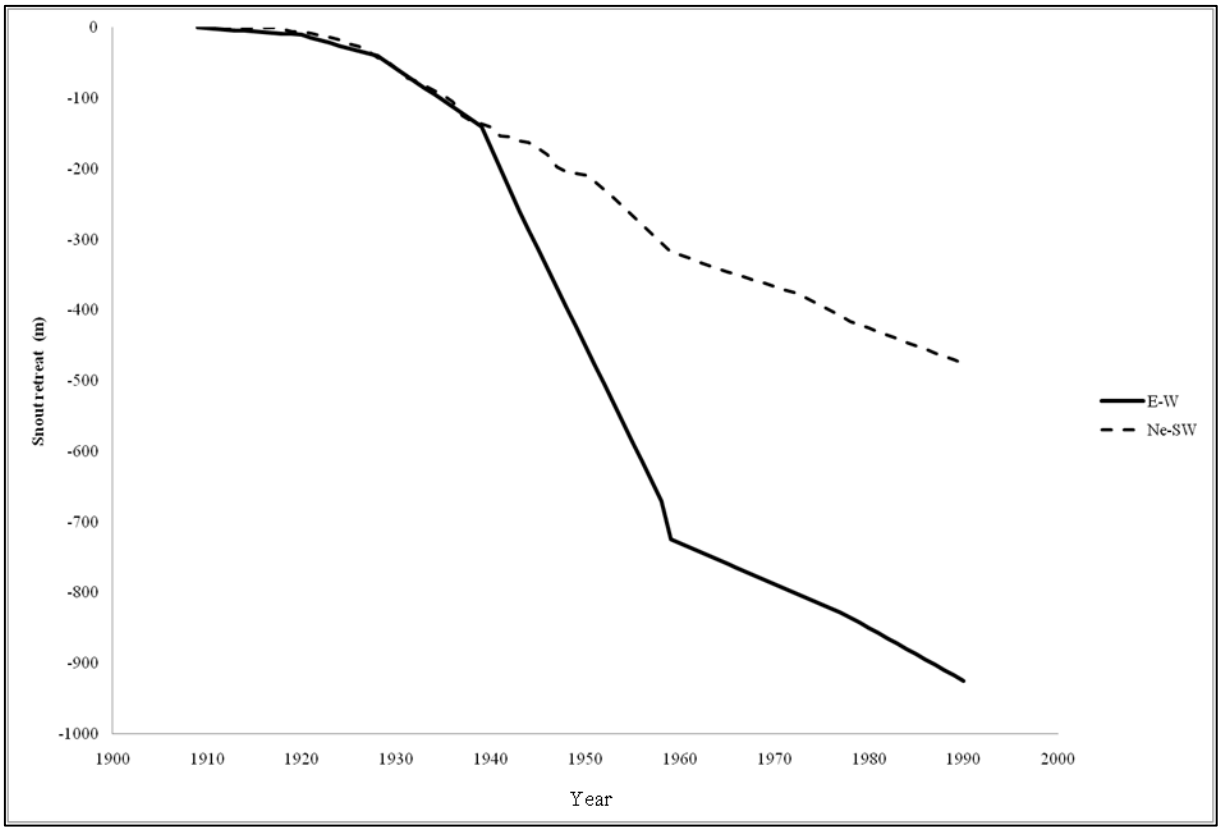

Figure 3.9 - Recession of the Kårsa glacier in both North East to South West and East West directions between 1908 to 1990, adapted from Bodin (1991).

the Kårsa glacier (Svenonius, 1910) and the Kårsa valley started its life as "the best known U shaped valley in Sweden" (Holdar, 1959).

At the start of the 20th century the glacier at the head of the Kårsavagge consisted of two blocks of ice, the main glacier orientated roughly east west along the valley and a connected glacier adjoining from the South Western slope (Wallén, 1948). It covered approximately 2.6km^2 and between 1884 and 1908 there was no discernible shift in the glacier margin (Svenonius, 1910; Wallén, 1948). Post 1908 the glacier underwent a recession with the rate of retreat increasing through the first half of the century (Figure 3.8 and Figure 3.9). Thinning at an average of 1m^3 km^{-2} yr^{-1} in the lower reaches was estimated by Ahlmann and Lindblad

(1940) between 1925 and 1939 but this was increased to 1.3 m^3 km^{-2} yr^{-1} by Schytt (1947) for the time period 1926 to 1943. The extent to which this disparity relates to differences of opinion is not known, however the recession recorded at the snout between 1939 and 1943 was over 120m (Bodin, 1991) suggesting that significant loss occurred after Ahlmann and Lindblad's (1940) investigation.

This increased rate of recession is generally put down to a combination of the increasing tempertures during the late 30's and the detachment the side glacier which occured sometime between 1926 and 1940 (Wallén, 1948; Wallén, 1949; Bodin, 1991). After the rapid retreat of the mid centuary rates slowed to around 5m yr^{-1} between 1959-1978 and have remained at about 8m yr^{-1} since (Bodin, 1991). Despite the recession and thinning in the lower regions, there was limited recorded change in the glaciers upper section (>1100m a. s. l.) over the whole of the 20th century (Bodin, 1991; Wallén, 1948). Due to its latitude and elevation the Kårsa's thermal regime is more similar to that of a polar glacier, with very limited ablation in its accumulation zone compared to temperate glaciers where ablation occurs over the whole area (Wallén, 1948).

The Kårsa glacier is highly responsive to climatological conditions and its response to the 20th century warming has been a decrease in total area from over 2.6 km^2 in 1908 to about 1.1km^2 by 2007 (Bodin, 1991) and a transformation from the transitional cirque-valley glacier described by Ahlmann and Lindblad (1940) to a temperate mountain cirque glacier (Figure 3.10). Should the rate of thermal increase remain the same it is estimated that the Kårsa glacier will have disappeared within 75 years (Plant, 2009).

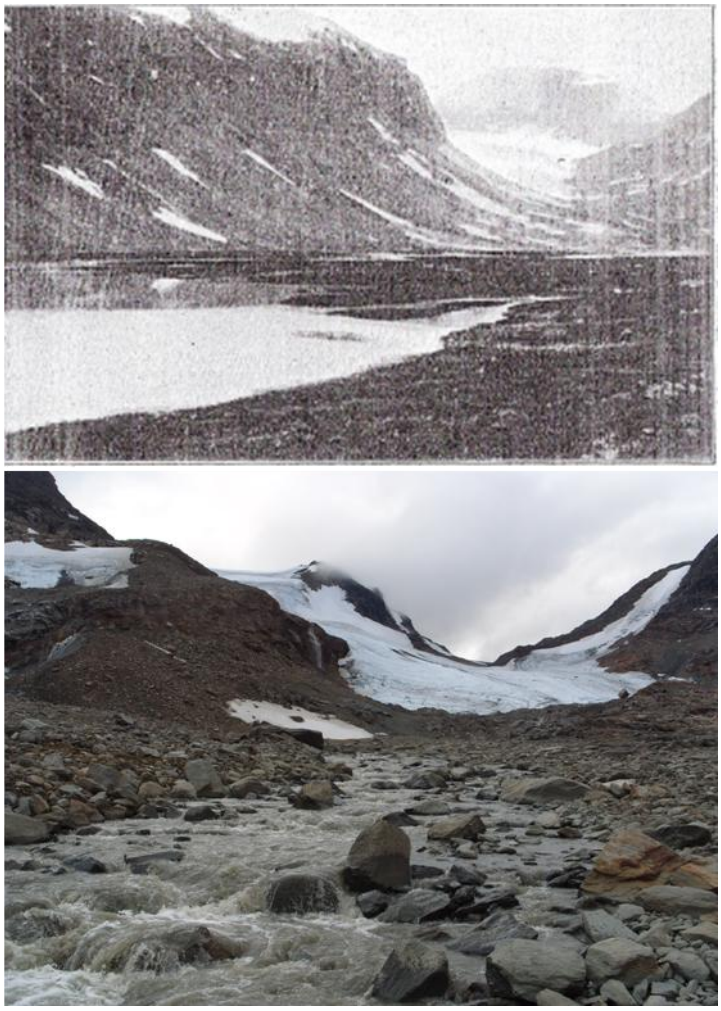

Figure 3.10 - Comparison of Kårsa glacier in 1908 to 2009. Top Picture from Svenonius (1910) glacier snout sits at ~K2, in the lower picture taken in 2009 by the Author the glacier has retreated to the top of the catchment.

Chapter 4 - General Methods

4.1 Meteorological variables

An Automatic weather station (AWS), sited at (68° 21' 36.2874N, 68° 21' 36.2874E) was used to collect air temperatures and precipitation data from the top of the catchment. These variables were logged continuously using a Campbell HMP35AC relative humidity probe, a Campbell CS700 Rain Gauge and a Campbell CR200 data logger.

Air temperature and rainfall in the lower valley was recorded using a Gemini Tinytag data logger housed within a radiation shield (68° 21' 3.5634N, 18° 25' 14.6634E), a Campbell ARG100 tipping bucket rain gauge at K2, and at Abisko Scientific research center.

4.2 Gauging stations

Stream gauging stations were installed at three points along the main Kårsa river channel over the duration of the two field seasons, at K1, K2 and K8 (Figure 3.1 and Figures 4.1- 4.3). Each gauging station recorded water column temperature, streambed temperatures at 0.05, 0.20 and 0.40 depth, stream stage and electrical conductivity (although not all data is used in the following chapters). In 2009 stage was monitored at two extra sites within the upper braided section B1 and B12 (Figure 3.3).

Figure 4.1 – Photograph of the river gauging station at K1. K1 is situated 0.13km from the glacier snout (68° 21' 37.605N, 18° 20' 56.0796E) at an altitude of 920m a.s.l. on the top plateau of the Kårsa valley, upstream of the top braided section and dominated by glacial flows.

Figure 4.2 - Photograph of the river gauging station at K2. K2 is situated 1.95km from the glacier snout (68° 21' 26.9886N, 18° 23' 33.1692E) and at an altitude of 742m a.s.l. It is downstream of the upper braids with flows sourced from glacier melt and snowmelt as well as groundwater inputs; it is just above a confluence with a large snowmelt stream.

Figure 4.3 - Photograph of the river at K8. K8 is 14.13km from the glacial snout (68° 20' 16.098N, 18° 38' 47.8962E) at 633m a.s.l. K8 marks a transition point between the region of the catchment with limited, shrub vegetation upstream and birch forest dominance downstream. Its position allows for the accumulated impact the lakes and large melt water inputs to be assessed.

Table 4.1 – Latitude and longitude of sampling sites along the main Kårsa river channel and the two points within the basin that air temperature was recorded. (AWS = Automatic weather station).

Site	North	East
AWS	68° 21' 36.2874"	18° 20' 58.632"
K1	68° 21' 37.605"	18° 20' 56.0796"
K2	68° 21' 26.9886"	18° 23' 33.1692"
K3	68° 21' 19.1406"	18° 23' 59.2512"
K4	68° 21' 18.1044"	18° 24' 0.4176"
K5	68° 20' 59.3988"	18° 24' 42.0186"
K6	68° 20' 3.2136"	18° 29' 54.1932"
K7	68° 20' 7.7958"	18° 35' 50.3556"
K8	68° 20' 16.098"	18° 38' 47.8962"
K9	68° 19' 49.5156"	18° 44' 26.9808"
Air temp	68° 21' 3.5634"	18° 25' 14.6634"

4.3 Water column and streambed temperature

Near bed water temperature was recorded at the main longitudinal sites K1-K9 (Table 4.1) from September 2007 to September 2009. The only exceptions to this were K7, where monitoring began on day 208 in 2008 and K5 where water temperature was only recorded during the summer field season of 2008 and 2009 (Table 5.4). Near bed water temperature was also recorded at a range of sites B1-B16 (see Figure 3.2) in the upper braided section of the river during the summer of 2008 (day 192 to 242) and 2009 (day 195-244) (Table 5.5). From September 2009 to June 2010 water temperature was recorded in a pool identified in the lower braided section (see figure 3.4) as a possible winter refugia for the local fish population.

Water temperature was measured continuously using Gemini Tinytag underwater temperature loggers, and at gauging stations also with Campbell Scientific 247 temperature-electrical conductivity probes. All temperature loggers were housed within radiation shields ~0.05m above the stream bed that allowed free circulation of water around the sensors. All temperature sensors were cross calibrated in a water bath before and after field usage. Correction factors were obtained using the methods of Evans and Petts (1997), which were within the manufactures overall accuracy range.

4.4 Stream discharge estimation

Water stage was monitored at the three gauging stations using Druck PDCR-1830 pressure transducers mounted in stilling wells. In 2009 two additional stage measurements were taken within the upper braids at sites B1 (Main glacial channel) and B12 (main snowmelt channel)

using stand-alone Tru-Trak WT-HR 1000 data loggers. Discharge estimates at the main gauging stations were obtained using the mass balance method (following Elder and Kattelmann, 1990) and at the two additional stations using the velocity area method (following Gregory and Walling, 1973). Stage discharge ratings curves were then constructed to provide continuous estimates of river discharge.

4.4. i) **Mass balance method**

A known mass of salt (NaCl) was dissolved in stream water and added to the river upstream of the gauging stations at sufficient distance to enable complete mixing to occur. Background EC was noted and following salt addition recorded every 2 seconds as the salt wave passed until it returned to the pre addition level. Discharge was then estimated following Equation 4.1 (Elder and Kattelmann, 1990; Hongve, 1987).

$$Discharge\ (Q) = \frac{(M \times K)}{(T_2 - T_1)(EC_{av} - EC_{base})} \qquad \textbf{Equation 4.1}$$

M = mass of NaCl added (g); K = conductivity constant of tracer (2.14 for NaCl); T1 = Time at start of salt wave; T2 = Time at end of salt wave; ECav = average EC under salt wave; EC base= background EC.

4.4. ii) **Velocity area Method**

The velocity araa method for discharge estimation was carried out following Gregory and Walling, (1973) and Kaufmann (1998). Each channel cross-section was divided into a minimum of 10 segments through which the discharge was estimated. The channel width was taken as a transect with point depth measurements made every 0.2m if the channel was more than 2m wide; or every 10% of the width. A segment was defined as a region of the cross-sectional area between two vertical depth measurements (Figure 4.4). Velocity was measured at 0.6 depth at all verticals using a Sensa RC2 electromagnetic current meter with 2 second readings averaged over 30 seconds. Average discharge through each segment was estimated using equation 4.2, and the total channel discharge was calculated as the sum of all the discharges across the cross-section (Gordon, 2004).

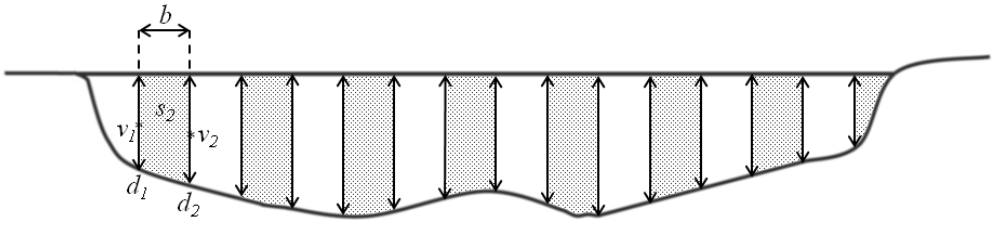

Figure 4.4 – Velocity area method for estimating discharge (modified from US EPA, 2004). Diagram shows measurements needed to work out discharge through segment 2 (S_2). v_1 & v_2 = velocity at 0.6 depth of verticals 1 and 2; d_1 & d_2 = depth of verticals 1 and 2; b =horizontal distance between verticals. Alternate segments are shaded for clarity. Depth and velocity at bank are both zero.

$$Discharge\ (Q) = \left(\frac{v1+v2}{2}\right)\left(\frac{d1+d2}{2}\right)b$$

Equation 4.2

Discharge (Q) using the velocity area method. v_1 & v_2 = velocity at 0.6 depth of verticals 1 and 2; d_1 & d_2 = depth verticals; b =horizontal distance between verticals.

4.5 Turbidity

Suspended sediment concentration at each site was estimated for samples of stream water. A pre-rinsed 500ml sample bottle was submerged to a depth of 10cm until filled. All samples were taken from well mixed stream sections. Samples were filtered in the field through pre-weighed Whatmann 40 ashless filter papers using a Nalgene hand-operated vacuum pump. Filter papers were air dried to remove excess moisture, then stored in sealed bags prior to analysis. On return from the field filter papers were dried overnight at 60°C then reweighted to determine suspended sediment weight. Suspended sediments were converted to mg L^{-1}.

4.6 EC

Electrical conductivity was recorded continuously at K1, K2 and K8 using Campbell scientific 247 temperature –electrical conductivity probes. Probes were checked and cleaned regularly to prevent sediment buildup. The probes measure conductivity over the range 0.005 to 7.5 mS cm^{-1} with an accuracy of ± 5% over the range 0.44 to 7.0 mS cm^{-1}.

4.7 Data logging

All gauging station and AWS sensors were scanned every 10s, from which 15 minute averages (totals for precipitation) were computed. Data was stored on Campbell Scientific CR10X data loggers at the gauging stations and on a Campbell Scientific CR200 data logger at the AWS. Tinytag data loggers recorded temperature every 15 minutes. All data loggers and TinyTags were synchronized prior to installation.

4.8 Hydrological sampling regime

4.8. i) **Snowpack sampling**

At the beginning of each field season (between day 176-209 see table 4.2) snow samples were collected from snow pits dug at various points within the upper catchment (>900m). Snow pits were dug to a depth at which bed material was encountered. In each pit samples were taken from identifiable snow layers, or where layers where not apparent in the middle of the top, middle and lower third of the pit. Unused 125 HDPE bottles were pressed into the snowpack to collect the snow. This snow was then allowed to melt and filtered following the stream water protocol.

4.8. ii) **Stream water sampling**

The hydro- chemical sampling program encompassed six sites (K1, K2, K4, K6, K8 and K9) along the longitudinal profile (Figure 3.1), sixteen sites within the upper braided section (B1-B16 see Figure 3.2) and twenty two within the lower braided section (A1-A12, C1-C10 see Figure 3.4). At least one water sample was collected every week at the longitudinal sites K1, K2, K4, K6, K8 and K9 (see table 4.2). Diurnal samples were taken at K1, K2 and K4 to characterize the variability in hydrochemistry associated with the daily cycles of meltwater generation. Samples were taken at low (06:00-09:00 h) and high flow (14:00-16:00 h). The size of the catchment (28km from top to bottom) prohibited a diurnal sampling effort at all but these top three sites. In the 2008 sampling season exploratory samples were taken monthly

from inputs around the catchment to identify key inputs. This was developed in 2009 with water samples taken every two weeks from sites across the top braided section (Table 4.2).

Individual samples were taken as follows. A 500ml HDPE bottle was rinsed three times with river water as a 30ml syringe. The bottle was filled for a fourth time and from this the sample was taken. 30ml of sample water was passed through a filter unit (pre-rinsed with distilled water) housing a 0.45μm Whatman cellulose-nitrate paper, ensuring all inside surfaces were wetted. This initial filtrate was discarded. Sample bottles (60ml HDPE) were then rinsed three times with 10ml of filtrate, by replacing the cap each time and shaking vigorously for 10 seconds. Bottles were filled with 55ml filtrate, leaving space for expansion during freeze storage. Samples were frozen to minimize any changes in hydro-chemical composition before analysis at the end of the summer. Electrical conductivity, Total dissolved solids (TDS), Resistivity (RES), pH, Oxidation-Reduction Potential (ORP) and Temperature were measured for unfiltered samples of river water using a Myron Ultrameter II.

Table 4.2 - Dates over both years (2008 - 2009) when water samples were taken at specific sites around Kårsavagge. K1- K9 are sites along the main channel (See figure 3.1). Upper braids refers to sites B1-B15 shown in figure 3.2. Lower braids refers to sites A1-A12 and C1-C10 shown in figure 3.4. Numbers in brackets refer to Julian day. * = no samples taken.

Sampling Date	K1 (AM & PM)	K2 (AM & PM)	K4 (AM & PM)	K6	K8	K9	Upper Braids (B1-B16)	Lower Braids (A1-A12, C1-C10)	Snow samples
2008									
1	27/06 (179)	*	*	*	*	*	*	*	27/06 (179)
2	04/07 (186)	04/07 (186)	04/07 (186)	05/07 (187)	05/07 (187)	01/07 (183)	*	*	*
3	11/07 (193)	11/07 (193)	11/07 (193)	12/07 (194)	12/07 (194)	12/07 (194)	*	*	*
4	18/07 (200)	18/07 (200)	18/07 (200)	19/07 (201)	19/07 (201)	20/07 (202)	18/07 (200)	*	*
5	26/07 (208)	26/07 (208)	26/07 (208)	27/07 (209)	27/07 (209)	27/07 (209)	*	*	27/07 (209)
6	01/08 (214)	01/08 (214)	01/08 (214)	02/08 (215)	02/08 (215)	02/08 (215)	*	*	*
7	08/08 (221)	08/08 (221)	08/08 (221)	09/08 (222)	09/08 (222)	09/08 (222)	08/08 (221)	*	*
8	17/08 (230)	17/08 (230)	17/08 (230)	15/08 (228)	15/08 (228)	15/08 (228)	16/08 (229)	*	*
9	23/08 (236)	23/08 (236)	23/08 (236)	24/08 (237)	24/08 (237)	24/08 (237)	*	*	*
10	30/08 (243)	30/08 (243)	30/08 (243)	29/08 (242)	29/08 (242)	28/08 (241)	*	*	*
11	06/09 (250)	06/09 (250)	06/09 (250)	07/09 (251)	07/09 (251)	09/09 (253)	*	*	*
2009									
1	25/06 (176)	25/06 (176)	25/06 (176)	27/06 (177)	27/06 (177)	25/06 (176)	*	*	25/06 (176)
2	02/07 (183)	02/07 (183)	02/07 (183)	04/07 (185)	04/07 (185)	30/06 (181)	*	*	*
3	10/07 (191)	10/07 (191)	10/07 (191)	11/07 (191)	11/07 (191)	06/07 (187)	*	*	*
4	15/07 (196)	15/07 (196)	15/07 (196)	16/07 (197)	16/07 (197)	18/07 (199)	15/07 (196)	*	*
5	22/07 (203)	22/07 (203)	22/07 (203)	22/07 (203)	22/07 (203)	20/07 (201)	*	*	22/07 (203)
6	29/07 (210)	29/07 (210)	29/07 (210)	02/08 (214)	02/08 (214)	04/08 (216)	01/08 (213)	*	*
7	05/08 (217)	05/08 (217)	05/08 (217)	07/08 (219)	07/08 (219)	*	06/08 (218)	*	*
8	11/08 (223)	11/08 (223)	11/08 (223)	12/08 (224)	12/08 (224)	16/08 (228)	10/08 (222)	13/08 (225)	*
9	21/08 (233)	21/08 (233)	21/08 (233)	23/08 (235)	23/08 (235)	25/08 (237)	22/08 (234)	*	*
10	26/08 (238)	26/08 (238)	26/08 (238)	*	*	*	*	*	*
11	01/09 (244)	01/09 (244)	01/09 (244)	29/08 (242)	29/08 (242)	30/08 (243)	*	*	*
12	07/09 (250)	07/09 (250)	07/09 (250)	08/09 (251)	08/09 (251)	10/09 (253)	*	*	*

4.9 Macroinvertabrate sampling

Quantitative macroinvertebrate samples were taken from six main channel sites (K1, K2, K4, K6, K8 and K9) and ten sites across the upper braided section (B1, B2, B6-B14). Sampling consisted of five 0.1m^2 Surber samples (250 μm mesh) replicates collected randomly from within a 15m reach. Where gauging stations were present all samples were collected downstream of gauges to avoid influencing equipment. All samples were transferred to a whirlpack bag and covered in a 70% ethanol solution. Table 4.3 shows dates on which these quantitative samples were taken in 2008 and 2009.

Quantitative benthic sampling was carried out following Lencioni and Rossaro (2005). Before each longitudinal benthic sample, 5 measures of water depth were taken and for each depth a velocity estimate at 0.6 depth was made using the Sensa RC2 electromagnetic current meter with 2 second readings averaged over 30 seconds. For each 0.1m^2 area within which a benthic sample was taken the percentage covered by substrate particles of different sizes was visually estimated: silt-mud (0.001<m), sand (0.001-0.02m), Gravel (0.02-0.05m), cobbles (0.05-0.20), boulders and bedrock (>0.2m). An estimate of moss % cover was also made.

Substrate at each site was investigated by measuring the b-axis lengths of 100 randomly selected particles. Particles were selected by walking transects and picking up the first particle contacted with an outstretched index finger. The phi index was used to separate sediments into size classes and this distribution was analyzed with Simpson's diversity index (following Brown *et al.*, 2006d). The bed component of the Pfankuch (PFANK) index was estimated (Pfankuch, 1975). This produces a score (the lower the score the higher the stability) based on

Table 4.3 – Dates over both years (2008-2009) when macroinvertebrate samples were taken. Dates in *italics* represent semi-quantitative sampling comprising combined kick net and 3 surber replicates; Other samples were quantitative comprising 5 replicate surber samples (see text and figures 3.1-3.5 for details).

Sampling Date	K1	K2	K4	K6	K8	K9	Upper Braids (B1-B14)	Lower Braids (A2, A5, A8, C1, C5, C7)
2008								
1	27/06 (179)	27/06 (179)	27/06 (179)	29/06 (181)	29/06 (181)	01/07 (183)	*	*
2	10/07 (192)	10/07 (192)	10/07 (192)	12/07 (194)	12/07 (194)	12/07 (194)	*	*
3	24/07 (206)	24/07 (206)	24/07 (206)	23/07 (205)	23/07 (205)	29/07 (211)	*	*
4	07/08 (220)	07/08 (220)	07/08 (220)	06/08 (219)	06/08 (219)	12/08 (225)	*08/08 (221)*	*
5	22/08 (235)	22/08 (235)	22/08 (235)	21/08 (234)	18/08 (231)	19/08 (232)	*	*
6	05/09 (249)	05/09 (249)	05/09 (249)	07/09 (251)	07/09 (251)	09/09 (253)	*	*
2009								
1	03/07 (184)	26/06 (177)	*	02/07 (183)	03/07 (182)	30/06 (181)	10/07 (191)	*
2	14/07 (195)	13/07 (194)	14/07 (195)	16/07 (197)	16/07 (197)	18/07 (199)	*	*
3	01/08 (213)	01/08 (213)	01/08 (213)	02/08 (214)	02/08 (214)	04/08 (216)	25/07 (206)	*
4	20/08 (232)	20/08 (232)	20/08 (232)	23/08 (235)	23/08 (235)	25/08 (237)	*	*13/08 (225)*
5	06/09 (249)	06/09 (249)	06/09 (249)	06/09 (249)	08/09 (251)	10/09 (253)	28/08 (240)	*

rock angularity, substrata brightness, substrate consolidation, scour and deposition and the extent of aquatic vegetation comparable between sites to asses channel stability.

At each main channel 15m sample reach (except K6 which prohibited this) average channel cross-section, wetted perimeter and average gradient were measured using an apney level, ranging poles and tape measure (Gordon *et al.*, 2004). Three ranging poles were used to keep a straight line and the angle between equivalent height positions on adjacent poles was measured. Poles were placed 0.3m apart or closer where there was a rapid change in gradient. Four cross-sections were taken at each site. A second set of four transects were taken, perpendicular the first to measure the upstream – downstream gradient at each site.

Benthic invertebrates within the lower braided section (Figure 3.4 and 3.5) were investigated through semi-quantitative sampling on one date in 2009 to inform a study of the diet preferences of the Arctic charr population. The ground water channel was sampled on 13th August 2009, the glacial channel the 14th August 2009. Each channel was sampled at 3 points (A2, A5 and A8; C1, C5 and C7 see Figure 3.4). Each sample incorporated three 0.1m^2 Surber sample replicates (250 μm mesh) and one run with a 0.1m^2 (250 μm mesh) pond n*et al*ong a 5m length of the each bank following forceful disturbance with a boot (as in Barbour *et al.* 2006). Substrate size was determined by measuring the b-axis of 100 substrate particles. Particles were selected by walking a transect across the channel and picking up the first particle contacted by each footfall following Gordon *et al.* (2004). The dry weight of Whatman 40 filter papers were recorded after drying overnight at 60°C. These were used to filter three 500ml samples of stream water, re-dried and reweighed to determine SSC. Channel width and depth was also recorded. At each sample site and at various points along

each braided channel stability was evaluated using the bottom component of the Pfankuch index (Pfankuch, 1975).

4.10 Arctic charr sampling

On 13th August 2009 an investigation of the postulated Arctic charr (*Salvinus alpinus*) population in the lower braided section was carried out. The entire 756m of the North East braid (sites A1-A10 Figure 3.4) was divided into 12 sample reaches. Each reach was electrofished using a back pack mounted ELT60-IIH Honda electro fisher was used in conjunction with kick nets (handled by field assistants) to stun and capture fish. Stop nets positioned at the top and bottom of each sample reach isolated the fish within, and the electro fisher operator moved from the downstream end to the upstream sweeping the anode back and forth below the water surface. Two sample runs were made in each reach. Upon capture fish were transferred to a within stream holding pen away from the sampling reach.

Each fish was anesthetized in a solution of 40mg L^{-1} clove oil, made up by mixing 5L of stream water with 2ml of a 1:9 mix of clove oil and ethanol following Woody *et al.* (2002). Measurements (fork length and weight) were taken for each of the 204 fish captured. One hundred individuals representing the range of sizes encountered had 3 scales removed for ageing. Non regenerated scales were removed from just behind the midline and just above the lateral line and placed between a cover slip and a slide. Tweezers were rinsed in ethanol between each sample.

In order to carry out analysis of Arctic charr diet fish were gut flushed. A flexible length of PVC pipe was attached to a 2ml syringe and used to inject water into the mouth of an anesthetized fish. The stomach contents were washed out into a small whirl pack bag and preserved in 70% ethanol. After measurement all fish were retained in a pen within the channel and released once they had fully recovered.

Along the length of each channel a hydrogeomorphic survey was conducted adapting the following units from the classes identified by Hawkins *et al.* (1993) and Hill *et al.* (2008): run, riffle, chute, scour pool, incised bank, incised bank pool, bar, side channel, tributary input and eddy (see Chapter 8 and Table 8.1).

4.11 Algae sampling

In 2009 bi-weekly algal samples (adapted from Ledger and Hildrew, 1998) were taken from K1, K2, K4, K6, K8 and K9. On each sampling occasion 3 similar sized cobbles were randomly selected. A 0.03m^2 section of each cobble was isolated with a plastic sheath and scrubbed with a clean hard toothbrush for 30 seconds. The toothbrush and sheath were rinsed with distilled water, and the washings transferred via a prewashed filter funnel into a new 60ml HPDE bottle and made up to 55ml to allow expansion during freeze storage.

4.12 Lake Bathymetry

A bathymetric survey was undertaken to estimate maximum depth, average depth and volume of the top lake, Bajimus Gorsajari (Figure 3.5). A Humminbird 587ci HD GPS-sonar kit was attached to a small rowing boat and transects were rowed criss-crossing the lake. At approximately 30m intervals waypoints recording latitude, longitude and depth were marked. These depths were interpolated using Surfer 8 from Golden software to give an estimate of lake volume ($0.018km^3$) and to create a bathymetric map. Discharge ($1.64m^3s^{-1}$) at the lake outlet was recorded using the velocity area method described earlier allowing an estimate of very approximate lake residence (130 days) time to be made.

4.13 Field data processing

4.13. i) **Field data evaluation and quality control**

The size of the catchment under investigation restricted the extent to which data loggers could be checked and downloaded. Despite this every time a logger was passed (~twice weekly) batteries were checked and probes cleared of debris. Estimates of instrumental and other errors are noted in Table 4.4.

River stages recorded at K1, K2, K4 and B1 and B12 were converted to discharge estimates with by comparison against stage-discharge rating curves. Rating equations were determined for each site over each year (Table 4.5 and Figures 4.5 – 4.7).

Table 4.4 - Measurement accuracies of electronic sensors used at stream gauging stations throughout the valley.

Variable	Instrument	Instrument Error (range)
Stream velocity	Sensa-RC2 electromagnetic current meter	0.005ms-1
River Stage	Druck PDCR-1830 pressure transducer	±0.1%
	Tru-Trak WT-HR 1000 dataloggers	±1%
Electrical conductivity	Campbell 247 conductivity and temperature probe	±5% (0.44 to 7.0 mScm-1)
Water temperature	Campbell 247 conductivity and temperature probe	±0.2°C (-35 to +48°C)
	Gemini Tinytag underwater datalogger	±0.2°C (-35 to +50°C)
Air temperature	Vaisala HMP35AC temperature and humidity probe	±0.2°C (-39.2 to +60°C)
	Gemini Tinytag Plus datalogger	±0.2°C (-35 to +50°C)
Precipitation	Campbell ARG100 tipping bucket rain gauge	0.05 mm
	Campbell CS700 Rain Gauge	±0.2°C

Table 4.5 - Stage : Discharge relationships at gauging stations. S = Stage (m), Q = Discharge (m^3 s^{-1}). K1, K2 and K8 are gauging stations along the main channel. B1 and B12 are stand alone pressure transducers in the upper braided section.

Year	Site	Rating equation	r^2
2008	K1	$Q = 125.17S^{3.0069}$	0.66
	K2	$Q = 34.393S^{3.0859}$	0.82
	K8	$Q = 13.817S + 2.141$	0.88
2009	K1	$Q = 31.665S^{3.5437}$	0.56
	K2	$Q = 19.678S^{1.5864}$	0.66
	K8	$Q = 22.621S + 3.4336$	0.83
	B1	$Q = 7.6074S - 0.6794$	0.90
	B12	$Q = 267.66S^{5.2433}$	0.66

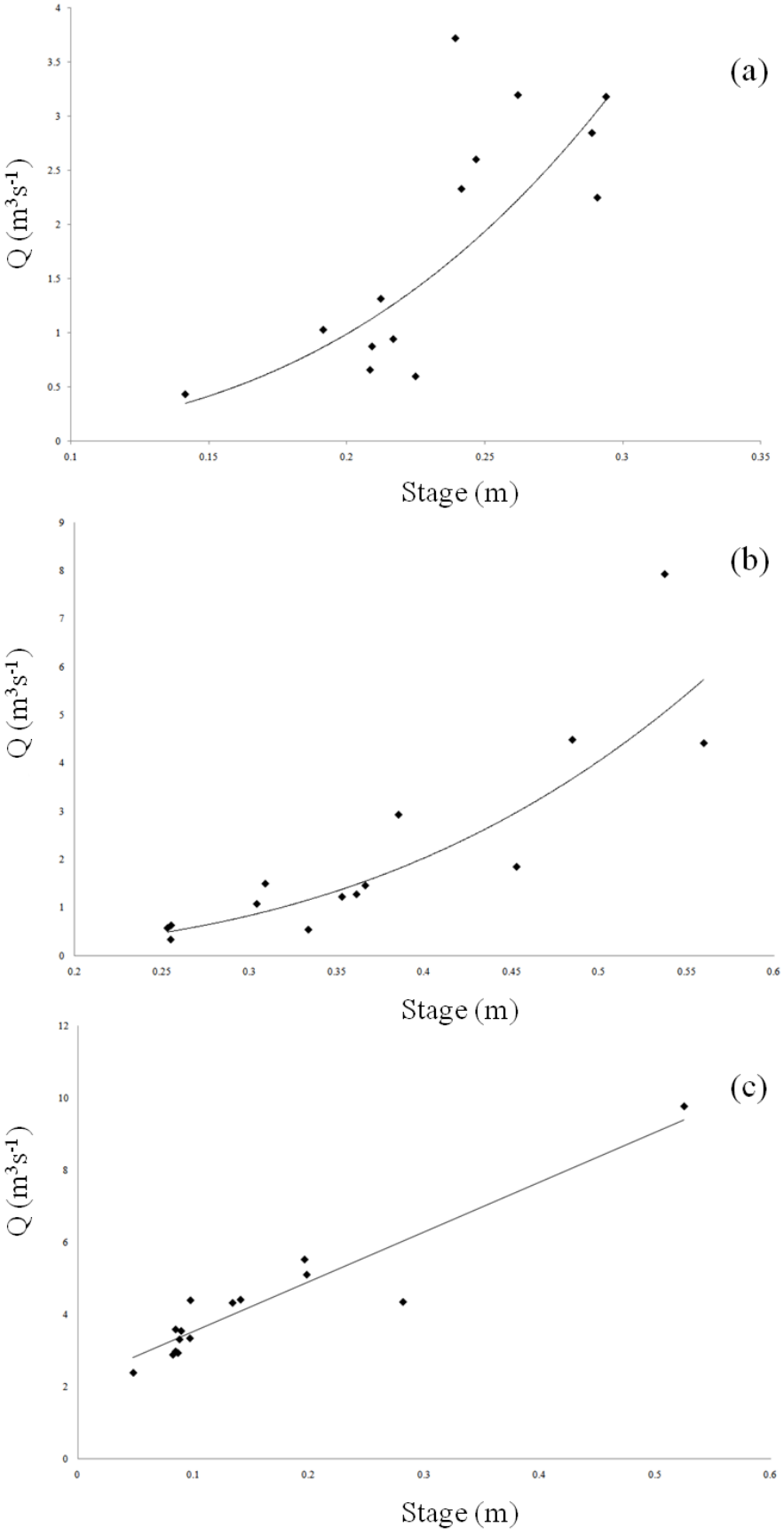

Figure 4.5 - Stage discharge relationships for gauging stations along the main channel in 2008. For equations and r^2 see table 4.5. (a) = K1, (b) = K2, (c) = K8.

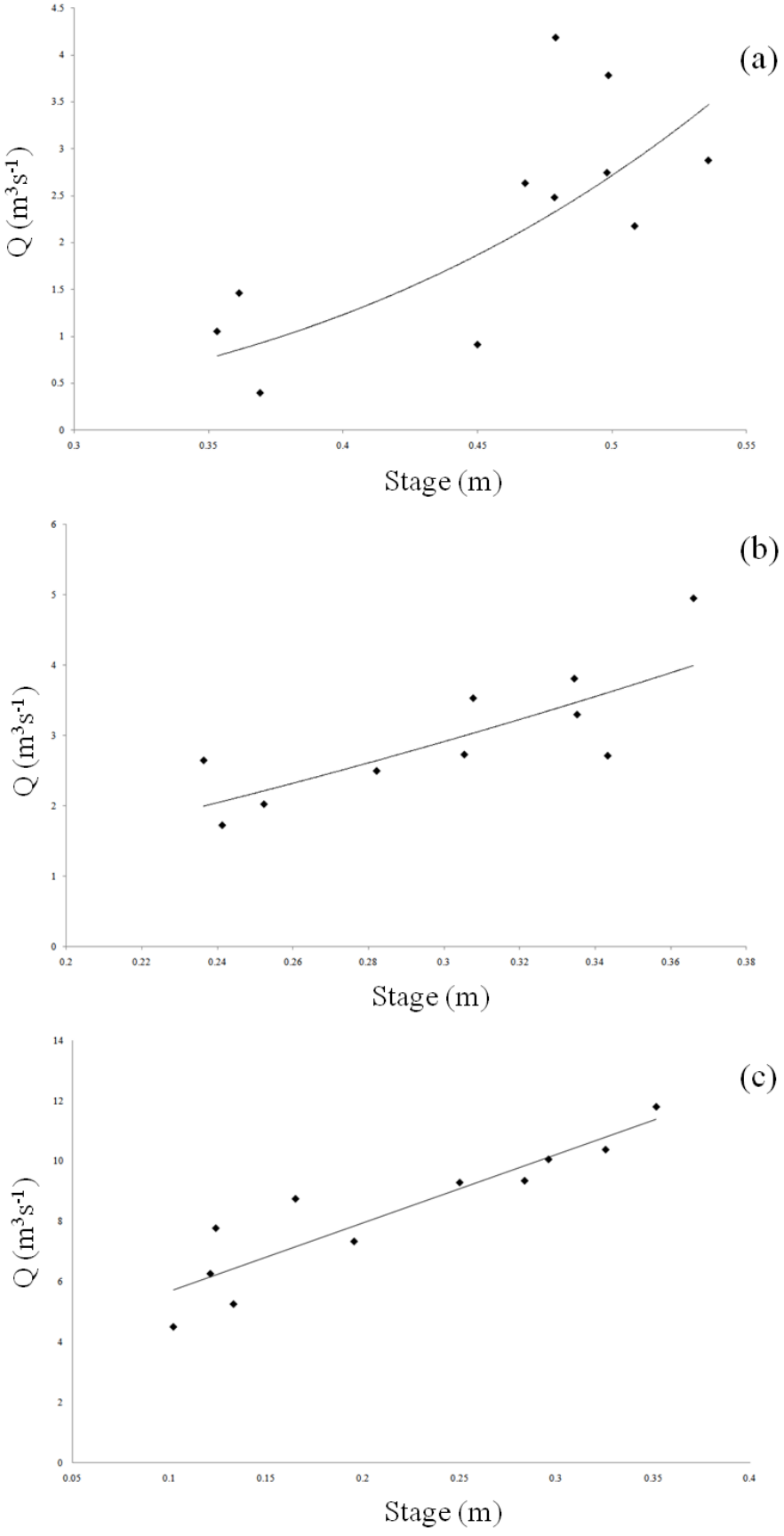

Figure 4.6 - Stage discharge relationships for gauging stations along the main channel in 2009. For equations and r^2 see table 4.5. (a) = K1, (b) = K2, (c) = K8.

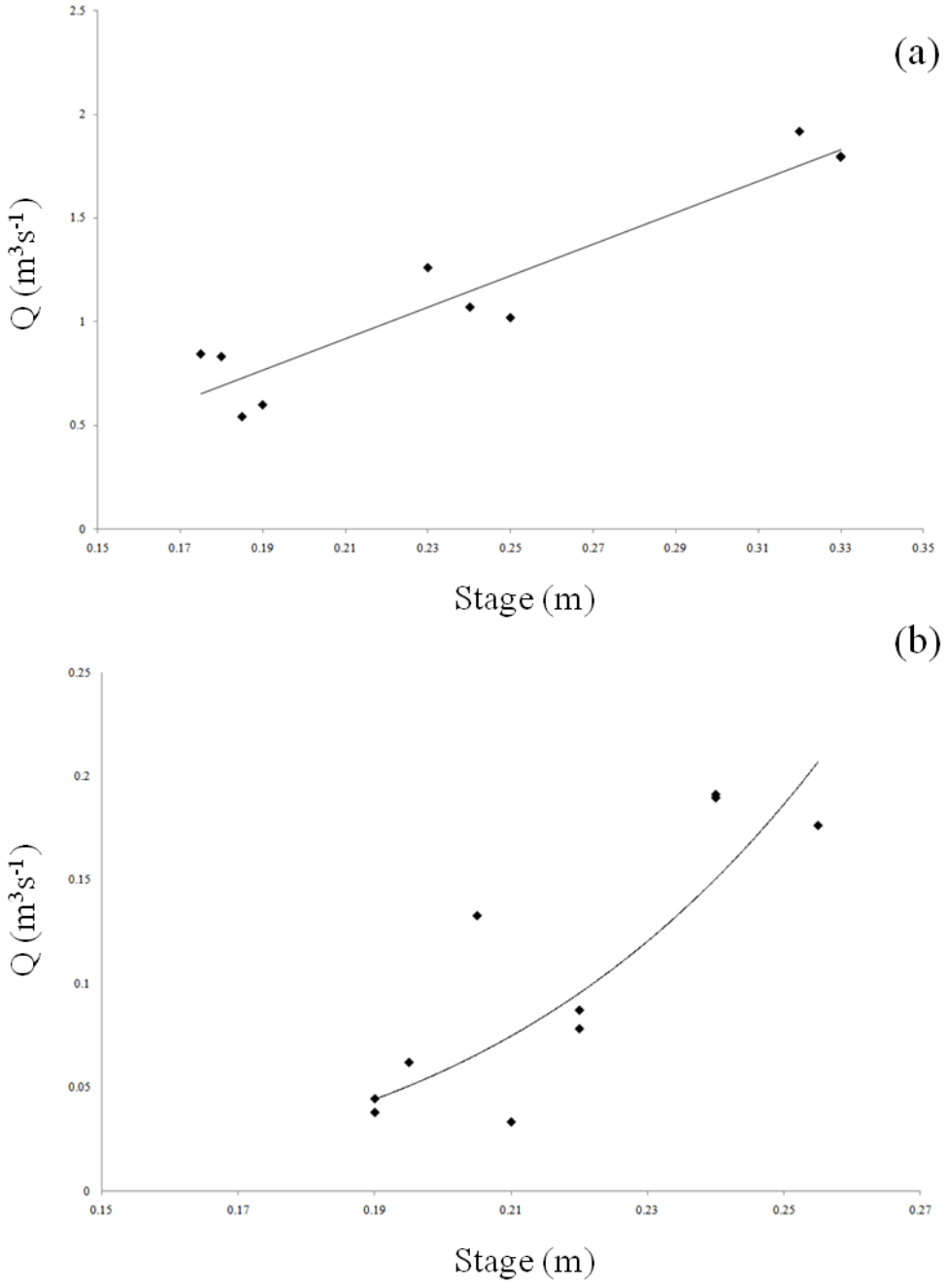

Figure 4.7 - Stage discharge relationships for selected channels within the upper braided section in 2009. For equations and r^2 see table 4.5. (a) = B1 the main glacial channel at the start of the upper braided section (b) = B12 the main snowmelt stream within the upper braided section.

4.14 Issues regarding loss of data from module

Raw data was downloaded weekly and potential issues with data identified and where possible remedied. Erroneous data points were identified and replaced by interpolating between previous and subsequent points. It is assumed that these were caused by interference with the sensors or corruption of logger storage. There was one instance of missing data that could not be interpolated due to the duration of the gap. This occurred at K8 in 2008 when the logger stopped working. It took 14 days to fix the issue and as a result discharge and EC for this period are missing.

4.15 Laboratory analysis

4.15. i) **Hydrochemistry**

Water samples were defrosted and stored in the dark at 4°C during analysis. 5ml of each sample was passed through a Dionex DX500 ion chromatograph using a IonPac CS16 to analyze for concentrations of major cations: Sodium (Na^+), Potassium (K^+), Magnesium (Mg^{2+}) and Calcium (Ca^{2+}). 5ml of each sample was also passed through a Dionex ICS2000 Ion Chromatograph using a IonPac AS11-HC to analyse for concentrations of major anions: Chloride (Cl^-), Nitrate (NO_3^-) and Sulphate (SO_4^{2-}). Concentrations of Bicarbonate (HCO_3^-) were estimated from charge balance deficits (following Hodson *et al.*, 2000; Brown *et al.*, 2006c). Calibration standards (0.05-10ppm) were made up from reagent grade compounds and deionised distilled water.

The analytical error inherent within these techniques has been shown to be ±5% (Brown, 2004; Hodson, 1994). Precision estimates for Ion chromatography for major cations are ±2.5% for Ca^{2+}, Mg^{2+} and Na^{+} and approximately ±10% for K+ (Hodson *et al.*, 2002a; Brown *et al.*, 2006c). Precision estimates for major anions range from <4% for SO_4^{2-} and Cl^{-} to up to 20% for NO_3^{-} (Hodson *et al.*, 2002a; Brown *et al.*, 2006c).

Silica concentrations were determined using a variation on the silico-molybdate spectrophotometric method (UCL, 1999; Neofotistou and Demadis, 2004). 10ml of each sample was mixed with 5ml 0.25M hydrochloric acid, 5ml Ammonium molybdate, 5ml Disodium EDTA and 10ml Sodium sulphite. This produces a moybdate blue colour. A UV-VIS spectrophotometer was used to compare absorbance at 700nm of sample solution with prepared standards of 0.1-20mgl^{-1}. Si concentrations determined using the silico-molybdate spectrophotometric method works in the range 0-75mgl^{-1}, has an accuracy of ±5% and has a high reproducibility (Neofotistou and Demadis, 2004; Stathoulopoulou and Demadis, 2008). For all analysis, ion and spectrophotometric, blank samples of deionised distilled water were evaluated every 10 samples.

4.15. ii) **Stable isotopes**

Determination of δD and $\delta^{18}O$ carried out in an Isoprime continuous-flow mass-spectrometer. Each sample was analysed twice to obtain an average. Internal precision for δD was usually better than 1.00‰ whilst the precision for $\delta^{18}O$ ranged between 0.08‰ and 0.12‰ (Morrison *et al.*, 2001). All results were expressed as delta values: δD (the enrichment of ^{2}H or *D* with respect to ^{1}H) and $\delta^{18}O$ (the enrichment of ^{18}O with respect to ^{16}O), in per mil (‰)

relative to VSMOW (Vienna Standard Mean Ocean Water). Deuterium (*D*) was the main isotope under investigation in this study as it is cheaper and quicker to analyse; ^{18}O was analysed from selected samples.

4.15. iii) **Chlorophyll a concentration**

Algal samples were processed following Ledger and Hildrew (1998). Samples were defrosted in the dark at 5°C. Defrosted samples were homogenized for 10-15 seconds and then filtered through Whatmann glass fiber (GF/C) filters. Filters were extracted overnight at 5°C in 90% acetone. Following centrifugation chlorophyll a concentration was estimated following the Monochromatic method (Aminot and Rey, 2001).

4.15. iv) **Benthic macroinvertebrate sorting and identification**

Each individual surber sample replicate (5 per site for each sample date) was sorted using a light microscope (x10 magnification) and organisms stored in 70% ethanol to await identification. Identification data from each replicate was then pooled to avoid variation due to small scale impacts (Brown *et al.*, 2006d). Keys used for identification were: Chironomidae of the Holarctic region : keys and diagnoses (Wiederholm, 1993); Aquatic Insects of Northern Europe Vol. 1. & 2 (Nilsson,1998); A Key to the Case-bearing Caddis Larvae of Britain and Ireland by (Wallace *et al.*, 2000); A revised key to the caseless caddis larvae of the British Isles with notes on their ecology (Edington, and Hildrew, 1995); A Key to the Adults and Nymphs of the British Stoneflies (Plecoptera): With Notes on Their Ecology and Distribution, (Hynes, 1995).

Non Chironomidae taxa were identified under a Zeiss Stemi-2000 stereo-microscope (6-50x magnification) and where ever possible Ephemeroptera, Plecoptera, Trichoptera were identified to species; most other taxa could only be taken as far as genus/ family.

Resident experts were consulted on identification of newly encountered species to produce reference set of voucher specimens used in subsequent identification. Resident experts were on hand to clear up further identification issues.

For samples containing >50 chironomids, a subsample of 50 were selected for identification, otherwise all individuals were included. To ensure these subsamples were representative small, medium and large Chironomidae within each sample were grouped. Individual Chironomidae were then randomly selected from each of these subgroups, in the same proportions as the group occurred in the whole sample (e.g. total number of Chironoidae in a sample = 500, number of small Chironomidae = 100 so number of small Chironomidae in sub-sample of fifty = 10).

Chironomidae were softened by placing them in a vial of 10% KOH solution which was transferred to a (60°C) water bath for 15-20min. Specimens were removed and rinsed before mounting in dimethy hydantoin formaldehyde solution for identification under a Nikon Optiphot-2 microscope (100-1000x). Where possible chironomids were identified to species or morphotype, otherwise they were taken to genus or sub-genus. Identification of benthic samples associated with the fish was much coarser and taxa were taken only as far as order.

4.15. v) **Fish laboratory analysis**

Arctic charr scales were mounted on slides and analyzed under a Nikon Optiphot-2 microscope (100-1000x) to identify and count annuli.

Gut flush samples were sorted as for benthic samples and identified to order. Contents were assessed using the numerical method (Hyslop, 1980).Where individual specimens could be identified, i.e. via head capsules these were counted, otherwise occurrence was noted. In the majority of cases a quantitative estimate of gut contents was possible.

Chapter 5 - Near-Bed Thermal Variability within Kårsavagge

5.1 Introduction

Stream water temperature is determined by the interaction of factors including water source (Brown *et al.*, 2003, Brown *et al.*, 2009a), discharge (Webb *et al.*, 2003), climate variables (Webb, 1998, Hannah *et al.*, 2004, Hannah *et al.*, 2008), geomorphology (Hawkins *et al.*, 1997, Cadbury *et al.*, 2008), aspect (Brown and Hannah, 2008, Arscott *et al.*, 2001) and bank cover (Arscott *et al.*, 2001). A comprehensive review of controls on river water temperature is provided by Webb *et al.*, (2008) and Caissie (2006). Spatial and temporal variability of these drivers gives rise to heterogeneity of thermal regimes across a range of scales (Mosley, 1983, ClarK *et al.*, 1999b, Uehlinger *et al.*, 2003, Brown and Hannah, 2008). As temperature is a key habitat variable, it exerts a major influence on the distribution and richness of aquatic biota, notably macroinvertebrate diversity and growth (Markarian, 1980, Vannote *et al.*, 1980, Milner *et al.*, 2001, Brown *et al.*, 2005, Haidekker and Hering, 2008). This is especially true in extreme environments where organisms live close to the limits of their thermal tolerance (Danks, 2007).

Water temperature in proglacial channels increases with distance from the glacier terminus (Brown *et al.*, 2006a; Cadbury *et al.*, 2008) and it is mediated by the impact of lakes and tributary inputs (Uehlinger *et al.*, 2003, Robinson and Matthaei, 2007, Brown and Hannah, 2008). This predictable longitudinal shift provides a key axis of basin thermal variability, one which has been used with success to explain the broad scale distribution of

macroinvertebrates downstream from a glacial source (Milner *et al.*, 2001). Kryal (glacially sourced) reaches are typically very cold (<4°C), stable with respect to temperature (Ward, 1994) and harbour a highly specialised and low diversity guild of macroinvertebrates dominated by Chironimidae (Ward, 1994, Milner *et al.*, 2001, Snook and Milner, 2001). Interactions between kryal streams and groundwater (krenal) or snowmelt (rhithral) sources that have contrasting thermal regimes produces a diverse matrix of thermal habitats enhancing species diversity at the basin scale (Brown *et al.*, 2006b, Robinson and Kawecka, 2007).

Recent publications have highlighted the extent of water temperature gradients present within the flood plain (lateral) and stream bed (vertical) and linked these to seasonal shifts in water source and connectivity (Ward *et al.*, 1999, Uehlinger *et al.*, 2003, Brown *et al.*, 2006a). Seasonally, lateral thermal variation can equal or exheed that observed longitudinally (Arscott *et al.*, 2001, Uehlinger *et al.*, 2003), yet lateral gradients have received limited attention and the few investigations that do contain elements of both lateral and longitudinal thermal variation focus on alpine rather than arctic systems. Though there are many parallels between Arctic and Alpine environments, the impact of latitude cannot be ignored (Irons and Oswood, 1992, Heino *et al.*, 2009). Irons and Oswood (1992) found greater exposure to sunlight during summer months produced higher average and daily maximum temperatures in an Arctic stream relative to two from the sub-Arctic. Therefore potentially longitudinal, lateral and temporal thermal variation within Arctic glACIAted basins may show a degree of divergence from patterns observed previously in Alpine basins at lower latitudes.

The vulnerability of water temperature to changes in climate or hydrology is enhanced in arctic and alpine basins due to the dominance of cryospheric water sources (McGregor *et al.*, 1995, Hannah *et al.*, 1999). Timing and extent of flow pulses associated with spring

snowmelt, diurnal fluctuations in glacier-melt and rainfall events are dependent upon different scales of climatic variability, as is timing and rate of the winter freeze (Barnett *et al.*, 2005, Hannah, 2007). Arctic climate warming occurred at twice the global average over the last century and air temperatures are predicted to rise by 7.5 °C by 2099 (Schiermeier, 2006, IPCC, 2007). The consequences of this shift on the hydrologic regime and, in turn, potential thermal diversity of Arctic basins may be dramatic, yet without investigations analysing and monitoring the extent of variation within contemporary systems projections are very uncertain.

5.2 This study

This paper aims to address the highlighted research gaps by assessing the extent of longitudinal and lateral water thermal variability by reporting on a high resolution (15min), multi-year (2007-2009) investigation of near bed arctic water temperature undertaken in a glacierized basin, Kårsavagge in Northern Sweden. Temperature is reported along the main channel from the glacial source to a confluence with a major river (nine sites, K1-K9 see Figure 3.1), from within the upper braided section close to the headwaters (B1- B16 see figure 3.2) and from one site within the lower braided section (A4 see figure 3.4) to investigate potential winter thermal refugia.

The aims are:

(1) To characterize water column thermal variation temporally, longitudinally and laterally within a glacierized arctic basin.

(2) To identify the extent to which this thermal variation is driven by different hydrological, climatological and spatially derived basin variables.

(3) To improve understanding of the processes driving the thermal diversity of surface waters within glacierized and more specifically arctic glacierized basins

5.3 Methodology

5.3. i) **Study Area**

The study was conducted in the Kårsavagge, a glaciated valley located partly in the Abisko National Park, Sweden (1823'01"E, 6820'01"N) 200km north of the Arctic Circle (Figure 3.1). The Kårsa River has a basin area of approximately 83.7km^2 and drains a small temperate glacier (1 km^2 about 1% of the total catchment) into the main Abisko River 18km downstream. Elevations of the valley floor range from 500 to 1100m above sea level (a.s.l) with surrounding peaks over 1550m. Local topography, latitude and proximity of Lake Torne interact to give the Abisko region its specific climate. The rain shadow cast by the high Abisko Mountains maintains an average annual rainfall of 300mm, making the Abisko region one of the driest in Sweden (ANS, 2009). At 68° north Abisko experiences the polar summer and polar winter. From 17 June to 19 July there is continual sun light, but between 18 December and 11 January the sun never rises above the horizon. These seasonal extremes in insolation are reflected in monthly average air temperature which ranges from 11°C in July to -12°C in January (ANS, 2009).

The Kårsavagge can be divided into three main sections: (1) the head waters; (2) the lower braids and the lakes, and (3) the river below the lakes (see Figures 3.1). The valley head is dominated by glacial melt water which forms a proglacial stream at the snout (900m a.s.l) that flows for 0.3km over gently sloping rocky moraine before dropping down to a plateau at approximately 820m a.s.l in a series of small waterfalls. The stream spreads laterally at this point and within this braided section snowmelt from two small tributaries is added (see figure 3.2). After 0.5km the channels coalesce into a single thread as the stream cuts down through a bedrock cut gorge to a second plateau (720m a.s.l) 2.3km from the glacial source. The ground between the glacier and the braids is devoid of vegetation except for sparse patches of hardy alpines. Mosses, grasses and sedges appear below 830m.

Three large snowmelt streams join the main river as it braids for a second time (see figure 3.4 and 3.5), above the start of the valley section two. Shallow gradients are maintained as the various (and highly mobile) channels enter the first of two ribbon lakes, 3.8km from the snout (Lake volume 18,463,887m3, approx. residence time of 129.5 days (personal measurement) see Figure 3.6). Between the two main lakes another major tributary enters the river, the outflow from Latnjajávri, a lake situated in a hanging valley 981m a.s.l. From start to finish section two is 9.5km long but elevation drops by only 60m. Vegetation of the second braided section comprises wet marsh species and cotton grass (*Eriophorum spp*.). By the mid-point of the first lake, 4.2km from the glacier snout willow (*Salix*) shrubs appear and at the end of the last lake a low growth birch, willow and aspen scrub has developed.

The final valley section before the Kårsa River joins the main Abisko River is characterised by steep rapids and large calibre bed material with flows exceeding 10 m^3s^{-1} during spring snowmelt. In this region, the tree line is at approximately 600m a.s.l. At the maximum extent

of tree line advance a birch/ willow scrub dominates but low birch forest takes precedence as altitude decreases.

5.3. ii) **Sampling Framework**

This paper is based on river temperature and hydrological data (1) spanning September 2007 to September 2009 from continuous monitoring sites along Kårsa River, (2) intensive thermal and discharge monitoring over two consecutive (2008 calendar day 179-244, 2009 calendar day 177-244) summer field seasons and (3) thermal monitoring at four sites over the winter of 2009. These three data sets allow the research aims to be addressed. Water and air temperature within the catchment were measured using Gemini TinyTag data loggers housed within radiation shields to prevent direct solar heating of the sensor. These data loggers scanned temperature every 10 s recording a 15 min (or 30 min overwinter) average.

Table 5.1 – Broad scale spatial and thermal information for sites along the main channel of the Kårsa river (K1-K9) and K3 a snowmelt fed tributary. Annual mean temperatures, total degree days, distance from source and altitude.

Site	Distance from snout (km)	Altitude (m)	Annual degree days (days)		Mean Temp (°C)	
			2007-08	*2008-09*	*2007-08*	*2008-09*
K1	0.13	920	154.0	159.7	0.11	0.07
K2	1.95	742	460.3	465.0	1.73	1.28
K3	na	730	-	654.2	-	2.45
K4	2.34	713	465.9	501.3	1.58	1.16
K5	3.05	704	-	-	-	-
K6	7.47	689	900.8	1017.2	3.31	2.75
K7	13.27	651	-	1162.9	-	4.39
K8	14.13	633	1036.2	1178.3	3.73	2.93
K9	18.31	424	1085.0	1271.1	2.75	3.32

In total 9 sites (K1-K9) longitudinally were equipped with data loggers (see Table 5. 1; Figure 3.1 and Table 4.1). K1, K2, K3, K6, K8 and K9 were monitored for the full duration of the 2007-2009 study. Monitoring at K7 began on day 208 in 2008 to take advantage of an extra logger and investigate whether the two different lakes had similar impacts. K5 was started on day 185 in 2008, removed over winter and re-installed on day 177 in 2009. Following cessation of the 2009 summer field season loggers at K1, K4 and K8 were replaced. In addition another logger was placed within a postulated groundwater fed pool (site A4 - see Figure 3.2) in the delta above the upper lake (Bajimus Gorsajavri). Continuation of high resolution thermal monitoring at these 4 sites was to investigate the potential winter habitat available to the population of Arctic charr recorded in Kårsavagge.

To investigate lateral near bed water thermal variation monitoring sites (B1-B15) were established laterally within the upper braided section; in channels deep enough to submerge fully the radiation shield housing. Monitoring the upper braided section ran from day 192 to 242 and day 195 to 244 in 2008 and 2009 respectively. Stations B1, B2, B3 and B6-B12 ran over both summers but Stations B13 and B15 replaced B4 and B5 in 2009 due to channel change. Air temperature was monitored using a TiniTag datalogger close to the north facing valley side opposite K5 and situated in the middle of the top braided section.

River stage (depth) was monitored continuously at sites K1, K2 and K8 with Druck PDCR-830 pressure transducers housed inside stilling wells connected to Campbell Scientific dataloggers. In 2009 river stage was also monitored at Sites B1 and B12, two channels within the upper braided section with Tru-Track WT-HR-1000 pressure transducers. Stage was scanned every 10s and averaged over 15 min intervals. Instantaneous measurements of discharge were carried out using the salt dilution method (Day, 1976) and velocity area

measurements in smaller channels. From these, stage-discharge rating curves were created to provide a continuous estimate of flow. Rainfall was measured at K2 using a tipping bucket (0.2 mm) rain gauge situated at ground level on the bank. Air temperature and precipitation data are also presented from an Automatic weather station sited 50 m from K1 taking 15 min averages with a 10s scanning interval and from the Abisko Scientific Research Station (ANS) 8km from the Kårsavagge confluence with the Abisko River, which recorded 30 min temperature averages and hourly total rainfall.

5.3. iii) **Data analysis**

Given the number of sites and amount of 15 min data, mean (total for precipitation) daily time-series are explored across the entire study period to elucidate patterns. Degree days (summed daily average temps above 0°C) have been calculated for each site. Eight periods across both field seasons representing the range of climatic conditions observed were selected for analysis of 15 min data: Period 1 (Julian day 182-186, 2008), Period 2 (Julian day 203-207, 2008), Period 3 (Julian day 208 to 212, 2008), Period 4 (Julian day 214 to 218, 2008), Period 5 (Julian day 238-242, 2008), Period 6 (Julian day 196-200, 2009), Period 7 (Julian day 204-209, 2009), Period 8 (Julian day 235-240, 2009).

For the selected periods, figures present high resolution temperature, discharge and precipitation data and tables give summary statistics to allow ready inter-site comparison. Temperature–duration curves are constructed to illustrate the percentage of time a temperature was equalled or exceeded at each location. Unlike summary statistics, temperature–duration curves present all data for a given period. This avoids problems of outlying values (in the case

of maxima or minima) or loss of information (mean, median, etc.), although there is loss of temporal context. The form of these curves depicts the nature of thermal characteristics as steep (low) gradient curves reflect high variability (thermal constancy).

Pearson's product moment correlation coefficients (r) are estimated for each season and period at each site to determine the instantaneous correlation between air and near bed temperature. However water thermal response to atmospheric forcing usually has an associated lag period and to take this into account cross-correlation functions (CCF) are computed to assess lags and identify the maximum correlation between near bed and air temperature up to 24 h.

5.4 Results

The following pages present water column thermal data from the 2008 and 2009 field seasons. A description of the timing of spring melt and winter freeze at main channel sites over 2008 and 2009 is given, followed by a description of the hydroclimatological context during the each field season. Water column thermal patterns are then presented, first longitudinally then laterally before the two are compared. Lastly the influence of rainfall on water temperature is described.

5.4. i) **Seasonal timings**

None of the main channel sites along the Kårsa River flowed perennially throughout the two years study period (Table 5.2), though K2 only dropped below freezing on 34 days, 33 of which occurred during the 2007-2008 winter. 2008, the only year for which every site has melt and freeze data illustrates the difference between the sites; K2 maintained above freezing temperatures the whole year with K6 have the next longest uninterrupted period above 0°C (204 days), even more than K9 (192 days) much lower down in the basin. The cumulative days frozen across both winters (07 and 08) confirm the thermal regimes of K2 and K6 don't fit the expected longitudinal pattern both accumulating fewer (15 and 174 days respectively) than sites further downstream. The pattern of the annual freeze was the same for both years with K1 freezing first followed by K4, K8, K9 and K6. K1 froze on day 283 in 2007 and 291 in 2008. All sites except K4 froze later in 2007 than 2008 with daily average temperature remaining above freezing at K6 until day 24 in 2009 (Figure 5.1).

Table 5.2 – Cumulative frozen period and consecutive open water periods at sites with overwinter data. **Days Frozen** = Number of days (to the nearest day) without flowing water at sites for which there is overwinter thermal data. Calculated as sum of 15min periods when average temperature was at or below 0°C. **Days uninterrupted open water** = consecutive whole days during each year with temperatures above 0°C (* indicates logger removed before 2009 winter).

Site	Days frozen Sept 07- Sept 08	Days uninterrupted open water 2008	Days Frozen Sept 08- Sept 09	Days uninterrupted open water 2009	Total days Frozen Sept 07- Sept 09
K1	127	120	243	120	371
K2	15	365	0	*	15
K4	113	118	160	197	273
K6	100	204	74	*	174
K8	110	141	183	158	294
K9	96	192	118	*	215

Excluding K6 and K2, the river melt out began at the lowest site, K9 (424m a.s.l) with K1 last to thaw. Timing was different between the two years, the 2009 melt season starting earlier with positive daily averages at K9 recorded on day 102 compared to 124 in 2008. The disparity between the two years decreased up the valley with K1 melting 4 days later in 2008 than 2009. Thermal patterns observed at K2 and K6 diverge from the general pattern as positive temperatures were recorded at both sites well into the winter period, and reappear very early in the spring. Despite being warmer, a diurnal temperature pattern was not observed at K2 or K4 before the other stations lower in the catchment, which is indicative of possible groundwater or lacustrine flows at K6.

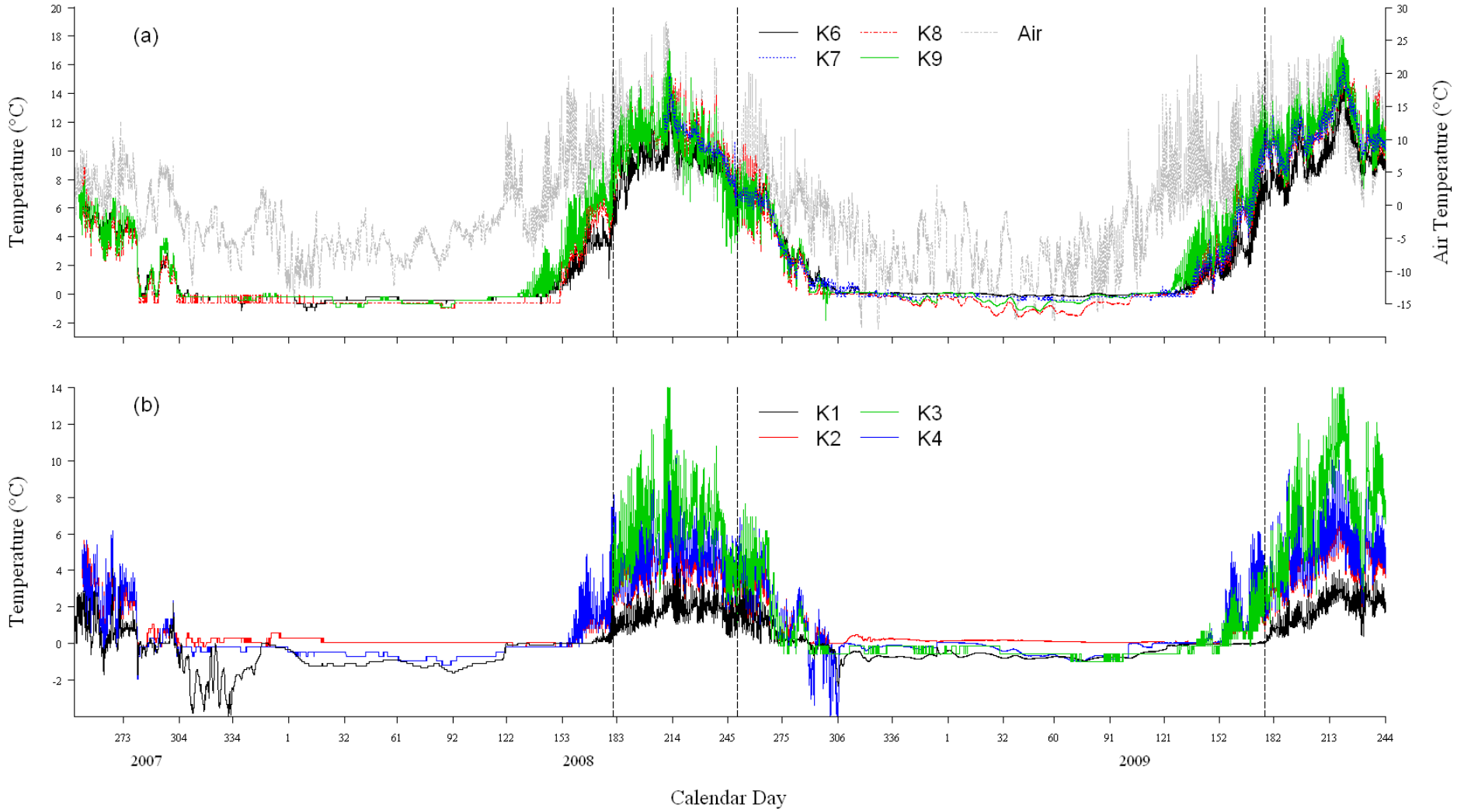

Figure 5.1 – Water and air temperature data for the entire study period from sites along the main channel of the Kårsa River. (a) Air temperature (on the second axis) and water temperature from main channel sites in the lower basin (K6-K9). (b) Water temperature from main channel sites (K1, K2 and K4) and K3. Vertical dotted lines show summer monitoring period.

5.4. ii) **Hydroclimatalogical context**

Average air temperatures differed during the two summer field seasons. Higher average temperatures were recorded during 2009 but the maximum, 27.87°C occurred during 2008 (Table 5.1 and Figure 5.2). Average air temperature patterns in Kårsavagge were similar at all sites during the study period (day 180 to 250) (Figure 5.2), though it was generally warmer in the lower valley, average temperatures increased from 7.5°C at the glacier snout to 10.4°C at the valley mouth, peaking on day 211 at the upper sites and 212 at those in the lower valley. All sites were subject to marked diurnal fluctuations in air temperature; however, cooler periods (e.g. days 204-207 in 2008), generally associated with precipitation events, dampened the amplitude of this daily variation.

Discharge values varied between sites with highest flows observed downstream at K8 (Table 5.3). The discharge record from 2008 illustrates the different extent of buffering by snow and ice melt between K1 and K2, with discharges at K1 showing lower variability as a result. In 2008 K1 recorded greater average discharge but had lower maxima than K2. This signal was not repeated during the wetter conditions of the 2009 melt season where K2 displayed higher maximum and average flows. The highest flows in the upper basin occurred at K during the 2008 melt season and were associated with rainstorms. Despite the significant impact of intermittent rainfall events, there is a general trend of reducing flows over both melt seasons, this is clearest during 2008 when rainfall was less. It is possible to assign periods of discharge for the 2008 melt season to the dominant hydrological processes: early season snow melt (ending around day 200), mid-season glacial melt (ending around day 220) and late season (reduced) glacial melt (Figure 2). The large diurnal fluctuation in air temperature throughout

the field season is reflected in a diurnal signal within the hydrographs. During the longest dry period, defined as 'no rainfall recorded' (day 212-222) there were significant ($p < 0.001$) cross-correlations between air temperature and discharge at all gauging stations, although the cross correlation function (lag time) de (in) creased considerably from K1 (ccf = 0.73, lag = 2.45 hr) to K8 (ccf = 0.41, lag = 19.00 hr). Precipitation events corresponded to increases in discharge but interrupted the normal cycle of melt water generation.

Table 5.3 – Descriptive statistics for discharge at gauged sites within Kårsavagge. K1, K2 and K8 sites along the main channel, B1 and B12 channels within the Mean, maximum (Max), minimum (Min) and standard deviation (SD).

Site		Mean (m^3s^{-1})	Max (m^3s^{-1})	Min (m^3s^{-1})	SD
K1	2008	2.39	4.41	0.32	0.79
	2009	2.17	4.28	0.81	0.58
B1	2008	-	-	-	-
	2009	1.33	2.77	0.09	0.61
B12	2008	-	-	-	-
	2009	0.11	0.24	0.02	0.04
K2	2008	1.89	5.51	0.26	0.87
	2009	2.82	4.89	0.46	0.91
K8	2008	5.33	10.00	2.79	1.94
	2009	7.46	13.74	4.18	2.37

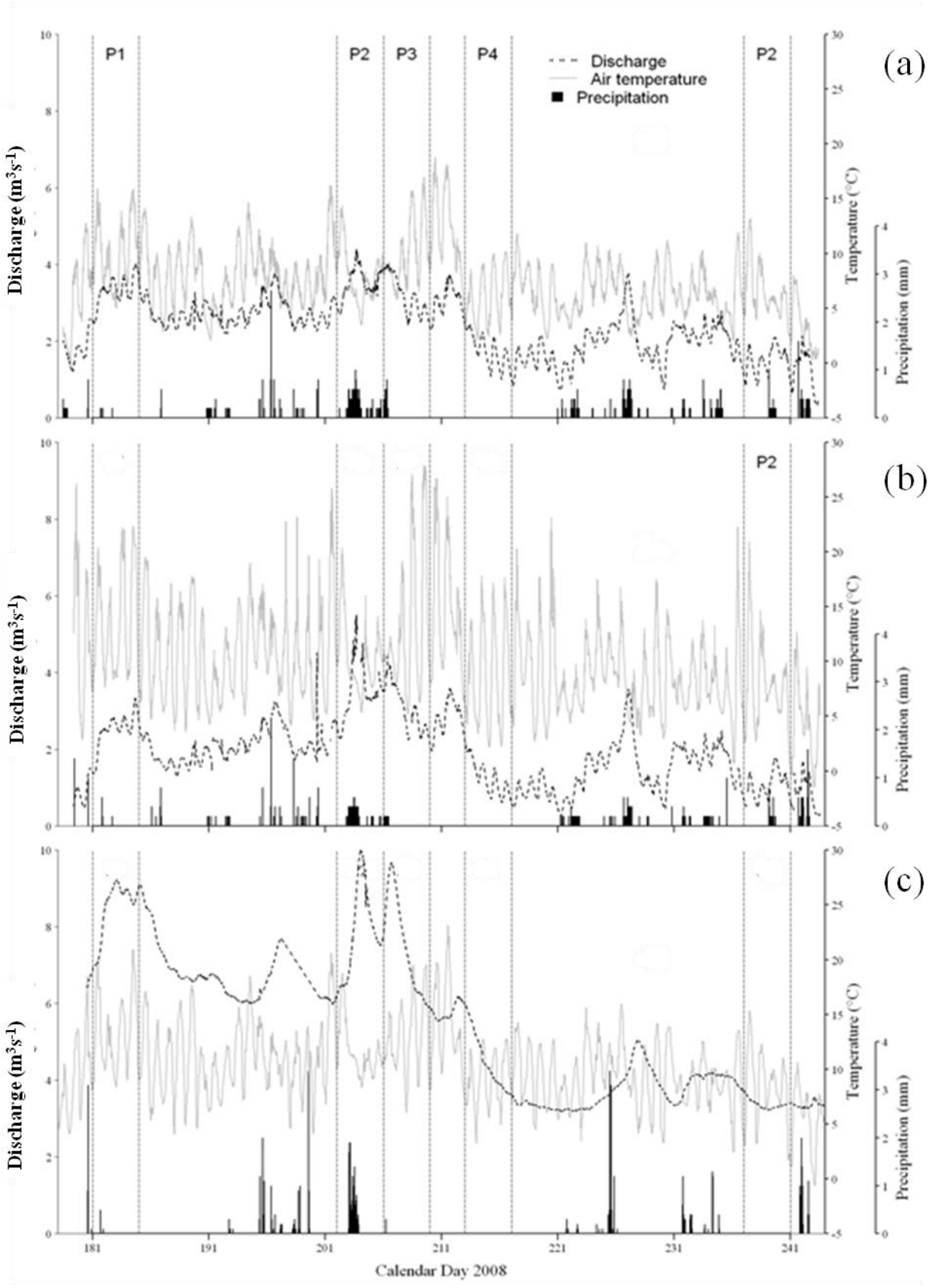

Figure 5.2 - Discharge, precipitation and air temperatures from gauging stations at (a) K1, (b) K2 and (c) K8 in 2008. Precipitation and air temperature data for K8 taken at ANS. Vertical lines denote Periods (P1-5) selected for further investigation later in the text.

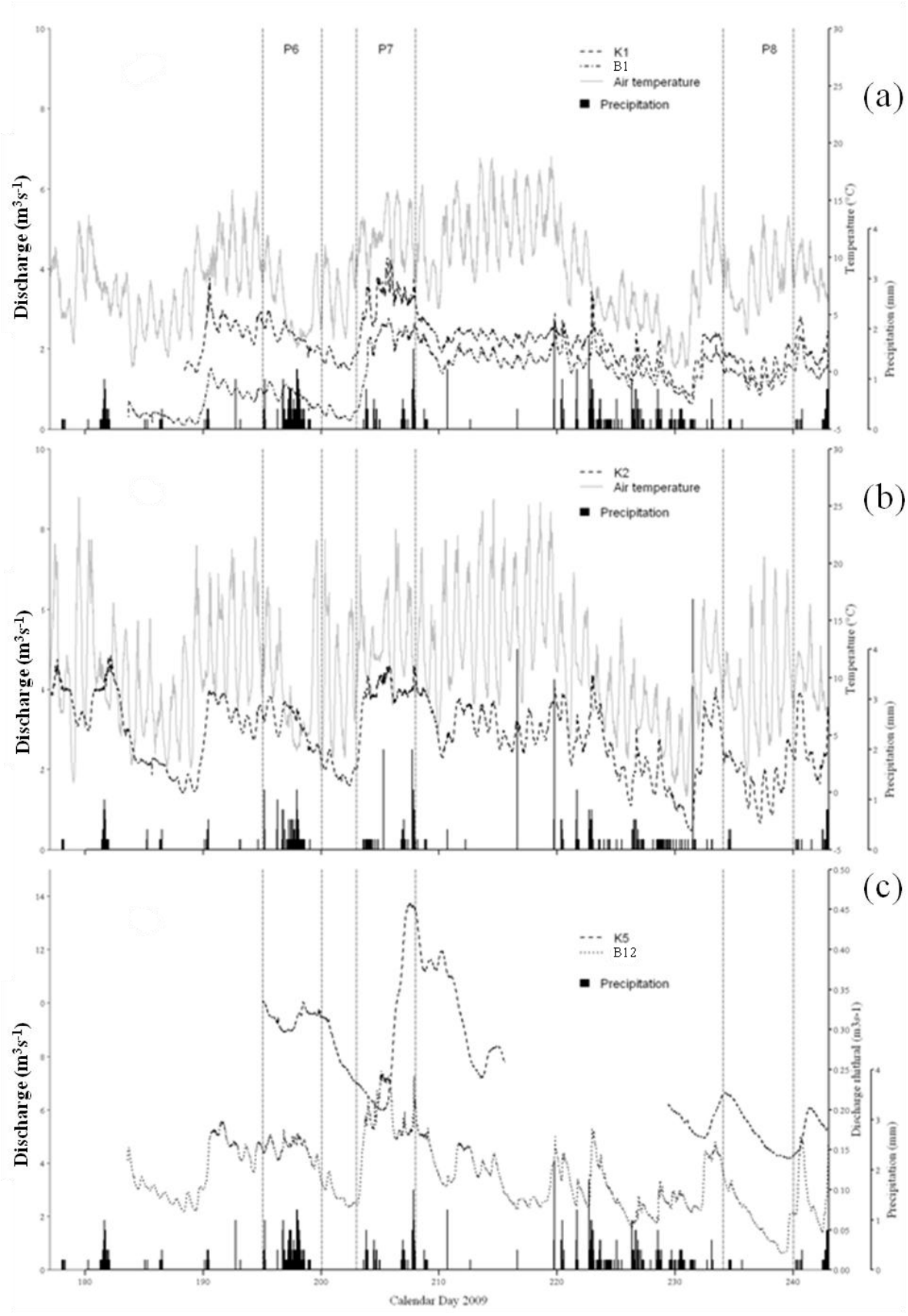

Figure 5.3 - Discharge, precipitation and air temperatures from gauging stations at (a) K1 and B1, (b) K2 and (c) K8 and B12 (on secondary axis) in 2009. Precipitation and air temperature data presented on (c) taken at ANS. Vertical lines denote Periods (P6-8) selected for further investigation later in the text.

5.4. iii) **Longitudinal seasonal patterns**

Mean water temperature increased along the main glacial channel with distance from the glacier with an overall rate of 0.50°C km^{-1} in 2008 and 0.54°C km^{-1} in 2009. Each site displayed similar thermal patterns during the summers of the investigation (Figure 5.4 & 5.5 and Table 5.4). Daily mean water temperature increased steadily until day 210 after which it declined slowly. Diurnal water temperature fluctuation was observed to some degree at all sites but this cycling was damped at K1, (i.e. the site proximal to the glacial source) and at K6 and K7 (situated below outflows from the two lakes). A reduction in amplitude of diurnal cycling at all sites was associated with longer duration precipitation events.

Table 5.4 – Descriptive statistics for near bed water temperature and cumulative degree days for sites longitudinally within Kårsavagge (K1-K9) between 20th June and 1st September, in 2008 and 2009.

Site	Mean (°C)		Max (°C)		Min (°C)		SD		Degree days (days)	
	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009
Air	9.35	10.59	27.87	25.78	-1.50	-0.35	4.93	4.87	707.6	817.4
K1	1.65	1.67	4.41	4.02	0.00	-0.01	0.75	0.91	121.4	129.3
K2	4.27	4.41	9.77	9.04	0.57	0.70	1.59	1.56	317.7	339.2
K3	6.54	7.37	14.12	15.24	1.84	0.69	2.15	2.82	446.4	534.8
K4	4.69	4.85	10.57	10.04	0.94	0.57	1.71	1.77	349.8	373.5
K5	5.72	6.00	11.32	13.11	1.28	1.81	1.81	1.88	379.7	417.7
K6	8.75	9.26	13.75	15.47	1.07	3.74	1.94	1.88	651.4	719.7
K7	10.62	11.12	15.22	16.11	6.14	6.17	1.50	1.65	706.8	848.0
K8	10.44	11.25	17.00	17.86	3.90	5.37	2.21	2.20	783.8	866.0
K9	10.07	11.63	17.13	18.01	2.84	5.85	2.46	2.04	775.4	895.5

The pattern of temperature increase with distance is not linear and includes some regions of rapid thermal accumulation and others of thermal constancy. Mean temperature increased

rapidly between K1 and K2 (1.47 °C km^{-1}) and remained relatively high between K4 and K6 (0.82°C km^{-1}), implying a strong thermal influence of the upper braided section and combined effect of the lower braids and first lake on water temperature. The rate of water temperature increase reduces after K6, peaking at K8 in 2008 and K9 in 2009.

Table 5.5 - Descriptive statistics for summer near bed water temperatures and cumulative degree days for all sites where temperature was continuously monitored (K1-K9, B1-B15) within Kårsavagge. Data collected between days 192 to 242 in 2008 and days 195 to 244 in 2009. Cor. – correlation of near bed temperature with air temperature; r^2 of the air: water correlation.

Site		Mean (°C)	Max (°C)	Min (°C)	SD	Degree Days	Cor.	*(r^2)*
Air	08	9.83	27.87	-0.44	4.60	501.4	-	-
	09	10.93	25.64	-0.35	4.95	535.7	-	-
K1	08	1.94	4.41	0.64	0.61	98.8	0.48	*(0.23)*
	09	2.15	4.02	0.42	0.63	105.4	0.67	*(0.45)*
K2	08	4.67	9.77	2.28	1.38	233.3	0.71	*(0.50)*
	09	4.99	9.04	1.86	1.30	244.7	0.86	*(0.74)*
K3	08	7.25	14.12	2.83	1.86	362.7	0.70	*(0.50)*
	09	8.41	15.23	2.67	2.38	412.3	0.81	*(0.65)*
K4	08	5.14	10.57	2.51	1.56	256.8	0.81	*(0.65)*
	09	5.45	10.04	1.92	1.92	266.9	0.86	*(0.74)*
K5	08	5.72	11.32	1.28	1.81	379.7	0.87	*(0.76)*
	09	6.42	13.11	3.35	1.90	314.5	0.71	*(0.51)*
K6	08	9.66	13.75	7.52	1.08	483.0	0.52	*(0.27)*
	09	10.16	15.47	7,52	1.57	4.97	0.54	*(0.30)*
K7	08	11.11	15.22	9.17	1.14	355.14	0.65	*(0.42)*
	09	11.70	16.11	9.37	1.50	577.4	0.51	*(0.26)*
K8	08	11.24	17.00	6.91	1.62	573.7	0.76	*(0.57)*
	09	12.00	17.86	7.90	1.91	587.8	0.74	*(0.54)*
K9	08	11.03	17.13	4.63	1.86	562.5	0.81	*(0.65)*
	09	12.33	18.01	7.35	1.98	604.1	0.76	*(0.52)*
B1	08	2.77	6.43	1.07	0.92	135.3	0.69	*(0.48)*
	09	3.11	5.65	0.71	0.84	152.6	0.83	*(0.69)*
B2	08	4.34	9.84	1.33	1.46	213.6	0.78	*(0.60)*
	09	5.04	9.34	0.51	1.56	246.5	0.76	*(0.58)*
B3	08	3.51	7.08	1.65	0.95	171.7	0.66	*(0.43)*
	09	3.38	6.24	0.81	0.94	165.91	0.82	*(0.68)*
B4	08	3.29	6.95	1.33	1.01	160.7	0.77	*(0.59)*
	09	-	-	-	-	-	-	-
B5	08	5.05	15.09	0.57	2.04	248.6	0.67	*(0.45)*
	09	-	-	-	-	-	-	-
B6	08	3.63	7.99	1.33	1.20	177.5	0.78	*(0.61)*
	09	4.31	8.52	0.57	1.40	211.4	0.84	*(0.70)*

Table 5.5 continued

Site		Mean (°C)	Max (°C)	Min (°C)	SD	Degree Days	Cor.	(r^2)
B7	08	4.25	10.01	1.99	1.24	208.0	0.77	*(0.59)*
	09	4.60	8.11	1.92	1.13	225.7	0.84	*(0.72)*
B8	08	8.62	15.95	2.59	2.06	426.3	0.75	*(0.56)*
	09	9.30	16.24	4.37	2.21	455.7	0.85	*(0.70)*
B9	08	8.44	12.53	2.59	1.36	416.9	0.66	*(0.44)*
	09	8.64	11.68	5.03	1.14	423.2	0.75	*(0.56)*
B10	08	8.76	15.76	2.78	1.98	432.9	0.80	*(0.66)*
	09	9.83	17.13	4.62	2.28	482.4	0.88	*(0.78)*
B11	08	5.03	13.95	2.34	1.70	247.0	0.75	*(0.56)*
	09	5.14	9.46	2.34	1.31	252.4	0.87	*(0.76)*
B12	08	7.67	14.66	2.77	1.84	379.1	0.75	*(0.56)*
	09	8.68	15.38	2.84	2.51	424.7	0.81	*(0.66)*
B13	08	-	-	-	-	-	-	-
	09	8.92	12.84	5.40	1.43	438.2	0.62	*(0.38)*
B15	08	-	-	-	-	-	-	-
	09	8.75	16.53	2.59	2.60	428.6	0.87	*(0.76)*

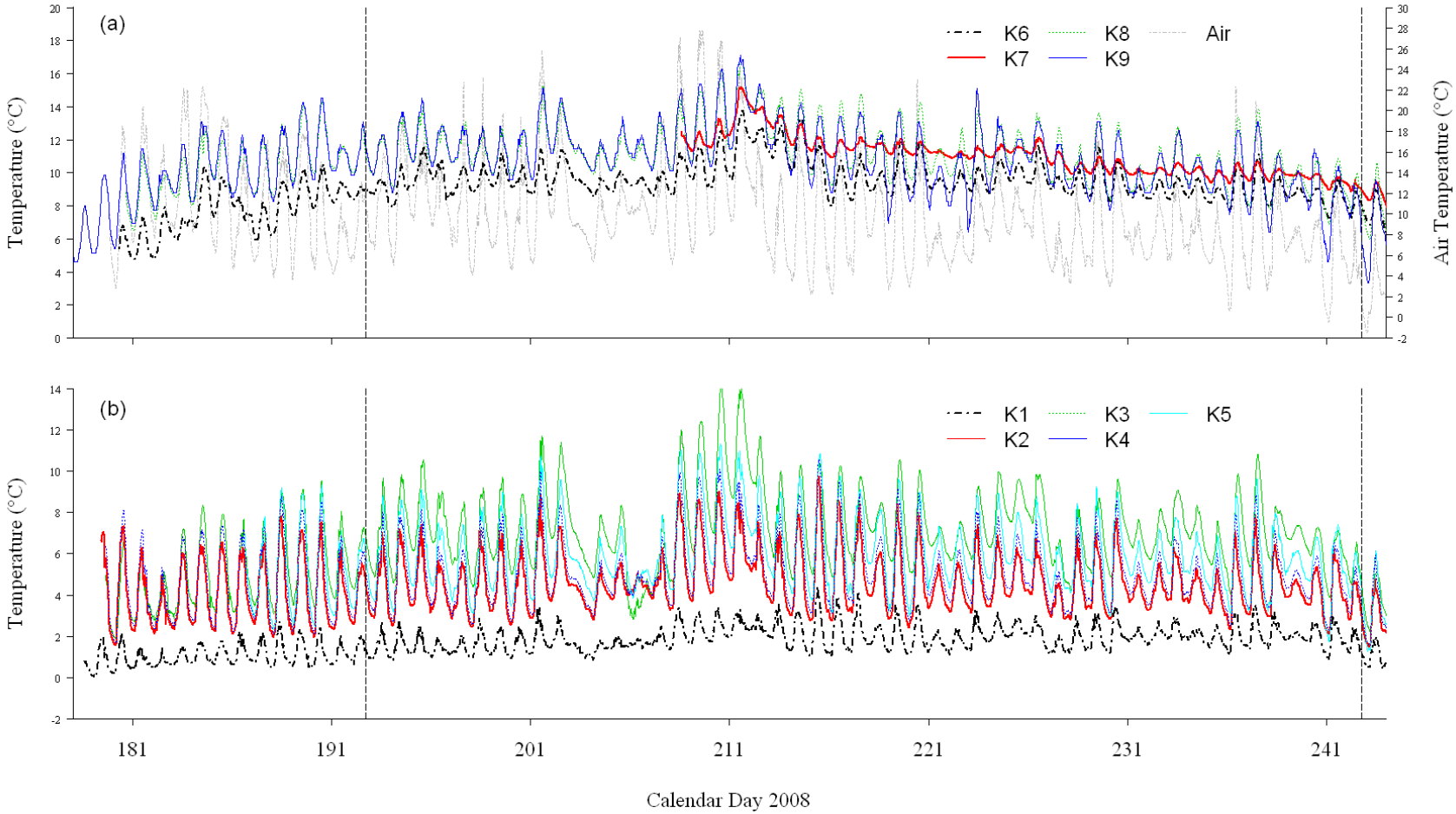

Figure 5.4 - Water temperature variation at the longitudinal monitoring sites during summer 2008. (a) Data from sites in the lower catchment (K6-K9) and air temperature on the second axis. (b) Data from sites in the upper catchment (K1-K5). Dotted lines delineate the period when the upper braided section were monitored (note the different y-axis on (b) for clarity).

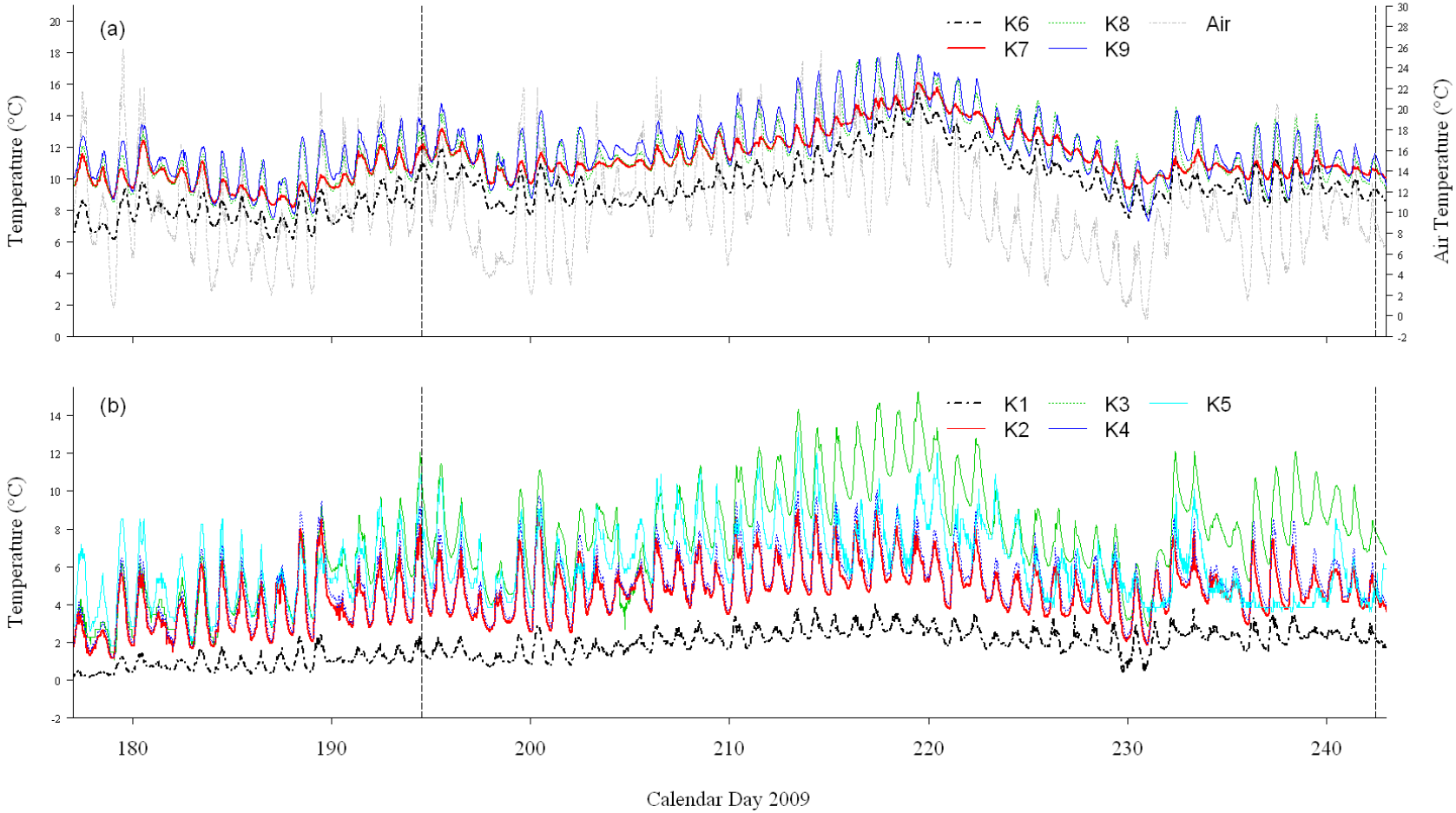

Figure 5.5 - Water temperature variation at the longitudinal monitoring sites during summer 2009. (a) Data from sites in the lower catchment (K6-K9) and air temperature on the second axis. (b) Data from sites in the upper catchment (K1-K5). Dotted lines delineate the period when the upper braided section were monitored (note the different y-axis on (b) for clarity).

Temperature duration curves reveal 4 main groupings of main channel sites (excluding K3 which is a snowmelt tributary see Figure 5.6). The relatively flat temperature duration curve of K1 signifies cold and thermally constant conditions. Temperature duration curves for K2, K4 and K5 illustrate the gradual warming and increasing variability with distance from the glacier terminus. K3 has steeper curve reflecting the higher thermal variability of this snowmelt sourced tributary. Lake Outlet sites, K6 and K7 show a degree of thermal buffering with very similar, relatively flat curves and thermal variability rises after the lakes at K8 and K9.

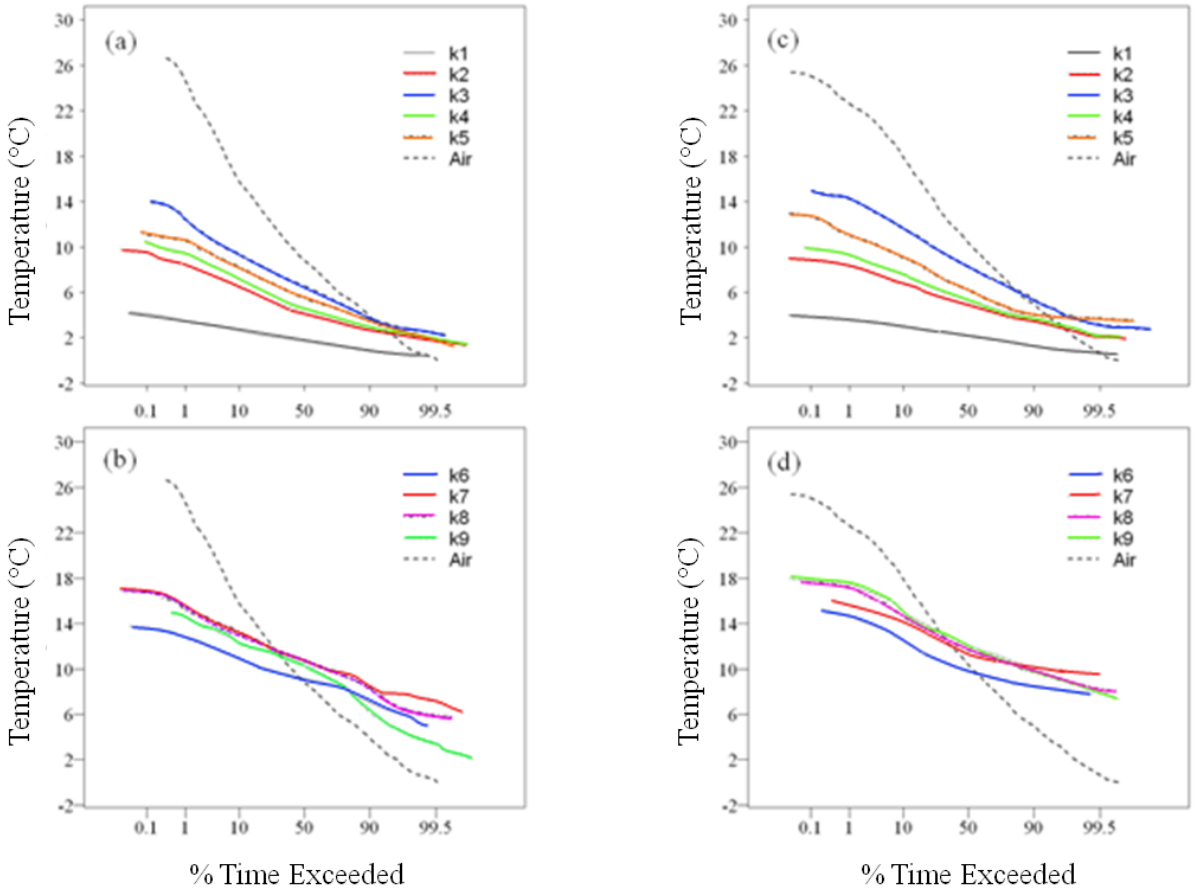

Figure 5.6 - Temperature duration curves of near bed water temperatures recorded at sites longitudinally with Kårsavagge during the summers 2008 and 2009. (a) K1-K5 2008, (b) K6-K9 2008, (c) K1-K5 2009, (d) K6-K9 2009. Air temperature is included on all plots for comparison.

Correlation coefficients and cross correlation factors (CCF) (See Table 5.4) between air temperature and water column temperature were highly significant ($p<0.001$) at all sites confirming the relationship between the two, but variation in the strength of these correlations illustrated the variability in the extent of this impact between sites. There was a general increase in air water correlations with distance from the glacier until the first lake with highest overall correlation ($r = 0.87$ [$p<0.001$]) found at K5 in 2008 and K4 and K2 ($r = 0.86$ [$p<0.001$]) in 2009 the lower braided section. The lowest correlation between water and air temperatures of 0.48 and 0.67 ($p<0.001$) and 0.52 and 54 ($p<0.001$) were found at K1 and K6 respectively, illustrating the impact of water source temperature and lakes in moderating the response of water to air temperature

5.4. iv) **Lateral seasonal patterns**

Thermal patterns within the upper braided section (see figure 3.2 and figure 3.3) were similar in terms of timing of fluctuations at all sites, though average temperatures and thermal ranges varied considerably. Near bed temperatures were coldest at B1 (average = 2.94°C) in the main glacial channel (Table 5.4, Figure 5.11 and 5.12) and warmest at B10 (average = 9.29°C) at the downstream end of a snowmelt fed channel. Channels within the braids can be grouped by water source (based on field observations) and these groupings (i.e. groundwater, glacial, snowmelt) are reflected in their thermal regimes. ANOVA with post hoc TUKEY analysis of mean daily temperature corroborate this a priori categorisation of sites into different thermal conditions (See Figure 5.10). Including longitudinal sites within this analysis illustrates the range of thermal conditions present within this region of Kårsavagge, as several of the lateral sites are not significantly different from longitudinal sites further downstream. Water column

emperature within the main glacial channel increased from 2.77°C and 3.1°C 1 at the start of the braided section (B1) to 4.25°C and 4.65°C at the downstream end in 2008 and 2009 respectively. Incremental increases were recorded at all loggers situated down this river section (excluding B11 in 2008). Average temperature at B11 was the highest recorded in the main channel in008 at 5.03°C and peaked at 13.95°C.

Temperature records from B2 and B12 illustrate the impact of aspect on thermal variability. Both channels are sourced from snowmelt yet average temperature recorded at B2, flowing from the north facing slope was lower and less variable than that at B12 which flowed from the south facing slope. Water from this source warmed up further before entering the main glacial channel with average temperature rising from 7.67°C at B12 to 8.76°C at B10. Greatest thermal variability was recorded at B8 with a range of 13.36°C.

Pearson correlation revealed highly significant ($p < 0.001$) correlation between air temperature and water temperature in all sites across the braids. The lowest correlation coefficients in 2008 were for at B1 and B9. B1 is the main glacial channel at start of braided section, showing a degree of fidelity to the source glacier temperature. However, the high and increasing correlation coefficients within the braids emphasizes the dominance of atmospheric heating in these small, exposed channels. Patterns in correlation coefficients shifted in 2009, with the glacial fed channels displaying much higher correlation with air temperature than in the previous year. The highest correlation in 2009 was observed at B15 (a mixed snowmelt and glacial channel) and B11 within the main glacial channel. The lowest air-water correlations were observed within the two groundwater fed seeps B9 and B11.

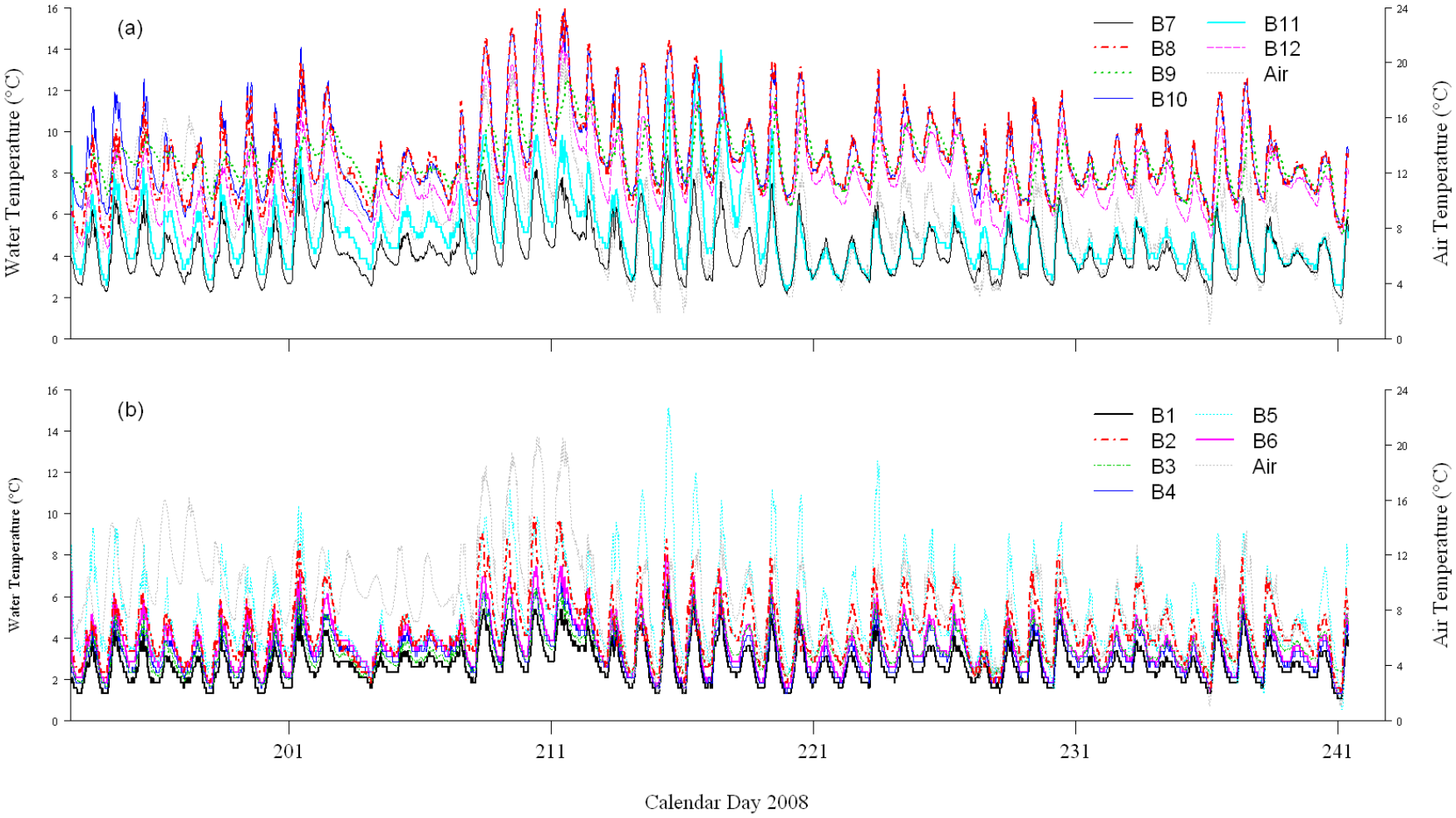

Figure 5.7 – Near bed water temperature variation at sites within the upper braided section of Kårsavagge during summer 2008. (a) Data from B7-B12. (b) Data from B1-B6. Air temperature is included on both plots for comparison.

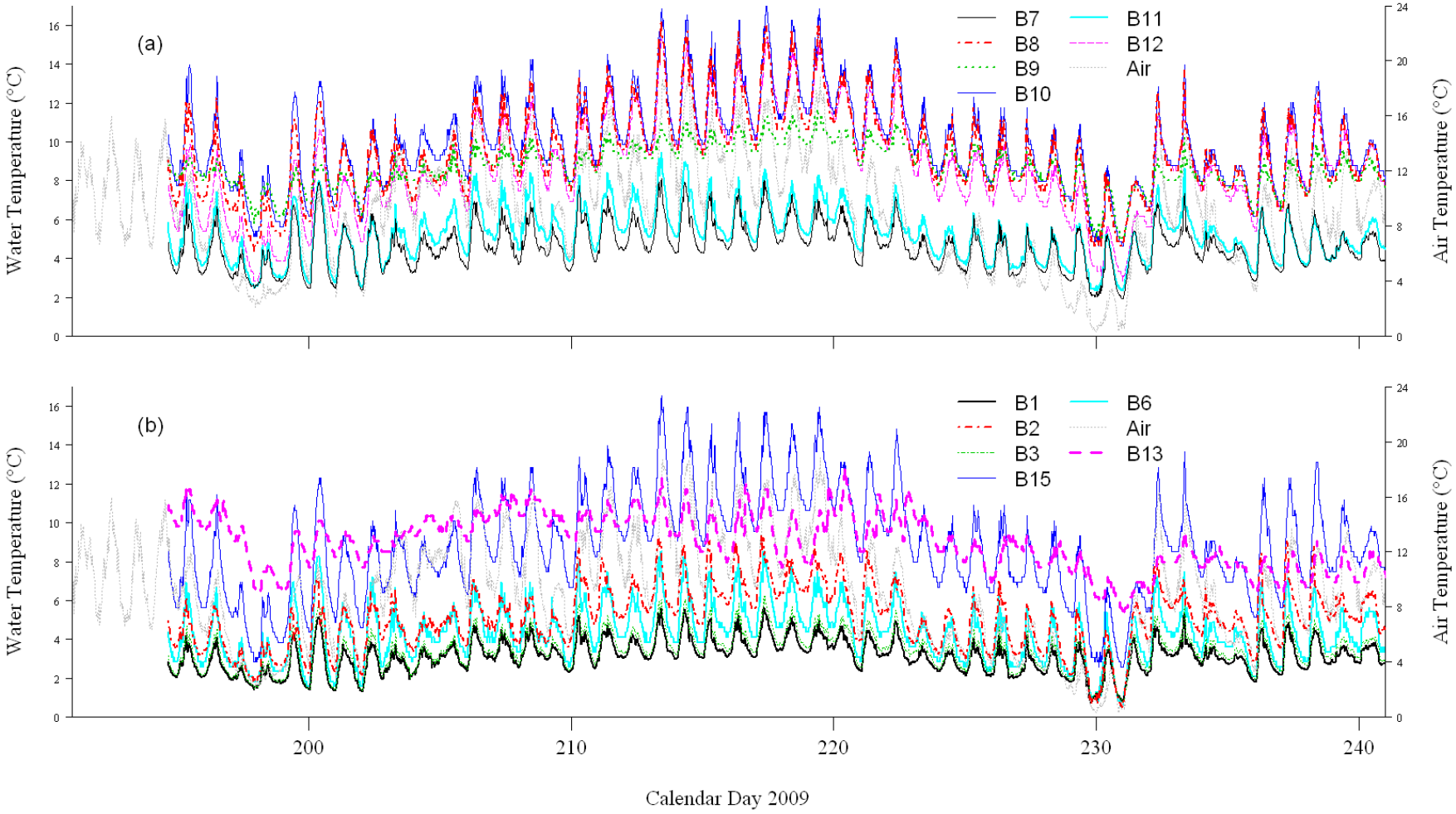

Figure 5.8 – Near bed water temperature variation at sites within the upper braided section of Kårsavagge during summer 2009. (a) Data from B7-B12. (b) Data from B1-B3, B5, B13, B14 and B15. Air temperature is included on both plots for comparison.

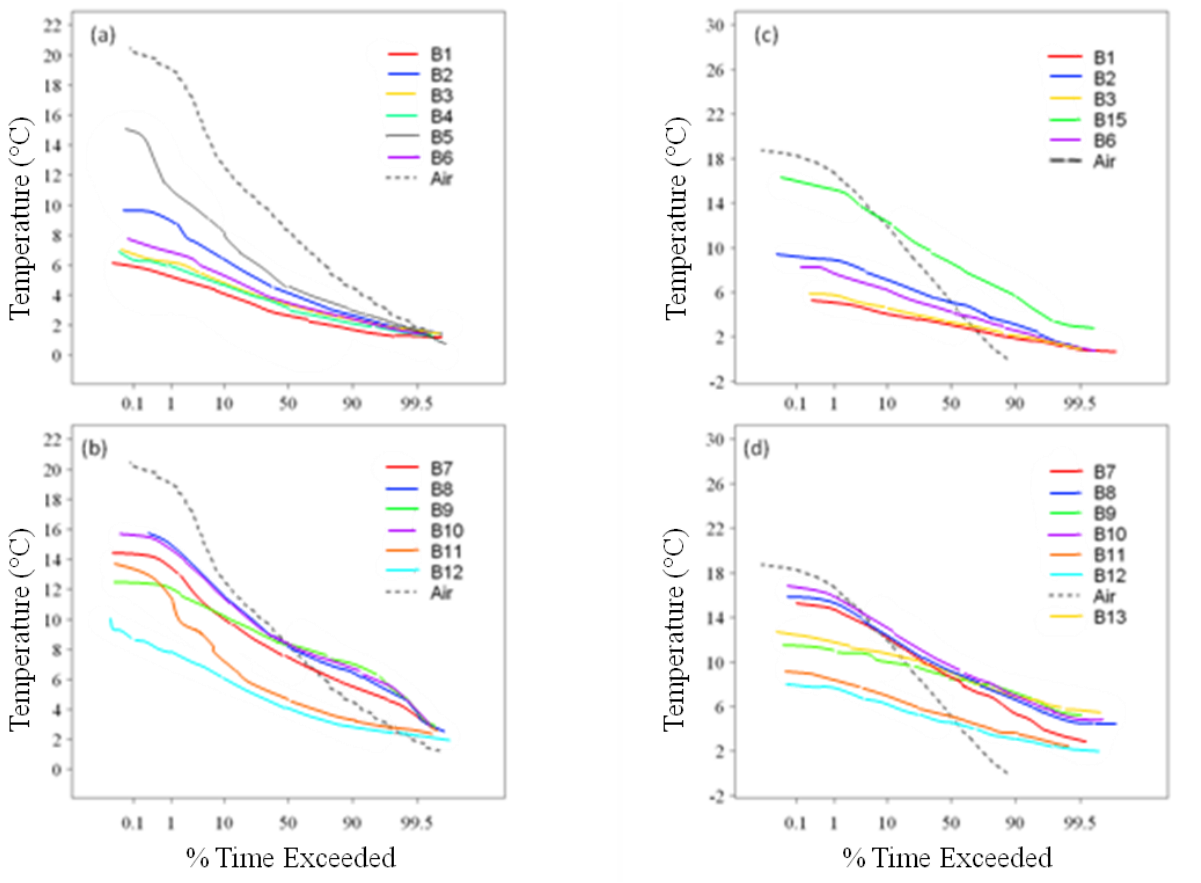

Figure 5.9 - Temperature duration curves of near bed water temperatures recorded at sites within the upper braided section of Kårsavagge during the summers 2008 and 2009. (a) B1-B6, 2008; (b) B7-B12, 2008; (c) B1-B6 and B15, 2009; (d) B7-B13, 2009. Air temperature is included on all plots for comparison.

Temperature patterns appear to confirm B9 and B13, as shallow groundwater seeps. The mean water temperature at these sites was amongst the warmest of any channel but the ranges are much lower than those recorded in any of the south facing snowmelt streams. The high maximum temperatures and large ranges recorded at B5, despite its glacial dominated source are due to the local channel morphology. It was sited in a narrow, relatively slowly flowing, shallow channel near the end of the braided section and therefore was particularly responsive to atmospheric forcing.

Precipitation events corresponded to a reduced thermal variability within the braids, and a suppression of diurnal temperature cycling. Thermal response to these events appears to be characterised by a reduction in daily temperature maxima rather than daily minima.

The range of thermal conditions within the upper braided section is illustrated by the variation in number of degree days accumulated at different sites. This ranged from 135.3 at B1 in 2008 to 432.9 at B10 in the same year (Table 5.5).

5.4. v) **Longitudinal – Lateral comparisons**

Groups which fall out of a TUKEY test on a one way ANOVA analysis of average daily temperatures (for details see Tables 5.6 and 5.7) are roughly aligned to postulated water source (see Figure 5.10). Snowmelt fed channels from the south facing slope are distinguished from those along the main glacial stem and the snowmelt fed channel from the north facing slope. Within these groups there is further distinction by distance from source. When longitudinal sites (K1 to K9) are incorporated into the analysis K6 is grouped with B10, K3 with B12, K2 and K4 could not be distinguished from the group containing B5 and K1 fell into the group containing B1.

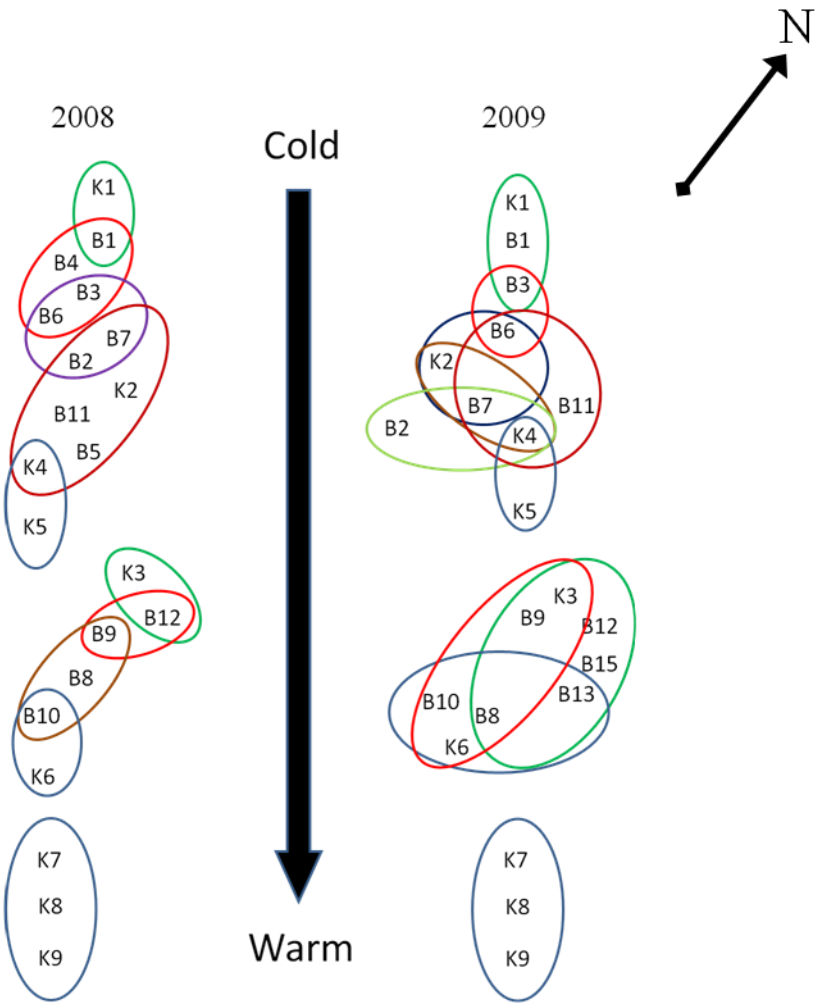

Figure 5.10 – Diagram illustrating similarity between thermal regimes of longitudinal (K1-K9) and upper braided (B1-B15) sites. Groups delineated using Post hoc groupings following ANOVA analysis of average daily temperatures (see Tables 5.6 & 5.7 for details). Sites within the same oval do not have significantly different ($p<0.05$) average temperatures. Data collected between days 192 to 242 in 2008 and days 195 to 244 in 2009.

Table 5.6 – Summary table for the one way analysis of variance carried out into average daily near bed temperatures for all sites where temperature was continuously monitored (K1-K9, B1-B12) within Kårsavagge between days 192 to 242 in 2008. d.f. = degrees of freedom; SS = sum of squares; S^2 = estimated variance.

	d.f.	**SS**	**S^2**	**F-Value**	**P-Value**
Site	19	7411.6	390.08	431.42	< 0.000
Residuals	1000	904.2	0.90		
Total	1119	8315.9			

Table 5.7 – Summary table for the one way analysis of variance carried out into average daily near bed temperatures for all sites where temperature was continuously monitored (K1-K9, B1-B15) within Kårsavagge between days 195 to 244 in 2009. d.f. = degrees of freedom; SS = sum of squares; s^2 = estimated variance.

	d.f.	**SS**	**S^2**	**F-Value**	**P-Value**
Site	20	9144.3	457.21	241.80	< 0.000
Residuals	987	1866.3	1.89		
Total	1007	11010.6			

5.4. vi) **Analysis of selected Periods**

To identify short term patterns and further elucidate water column thermal responses, eight, 5 day periods covering a range of hydroclimatological were selected for further analysis. These periods cover the range of conditions experienced within Kårsavagge over the two melt seasons.

Period 1) ***Day 182-186: Early summer, warm, high flows***

Average air temperatures were relatively high (14.38°C at K4) and river flow was above average at all gauging stations. A diurnal signal is present within the air temperature record but only a weak diurnal signal is observed within the discharge record (Figure 5.11; Table 5.8).This period contains three low intensity precipitation events, none of which appear to have had a significant impact on flows. Water column temperature was the coldest recorded within any of the selected periods, averages ranging from 0.98°C at K1 to 10.01°C at K9. Longitudinal thermal accumulation within this period displayed a unique pattern. Water temperatures increased on average by 2.87°C between K1 and K2, almost matching the 2.94°C between K4 and K6. In all other selected periods the K4 to K6 increase is >4.0°C and >0.6°C larger than the K1 to K2 increase. This disparity is mostly likely due to the thermal inertia created by the large volume of cold meltwater in the early season within the first lake compared to the small, highly thermally responsive channels in the upper braided section connecting K1 to K2. The second lake does not appear to display similar thermal inertia. Unfortunately, monitoring at K7, the second lake outlet did not begin until day 209; however, using data from other periods

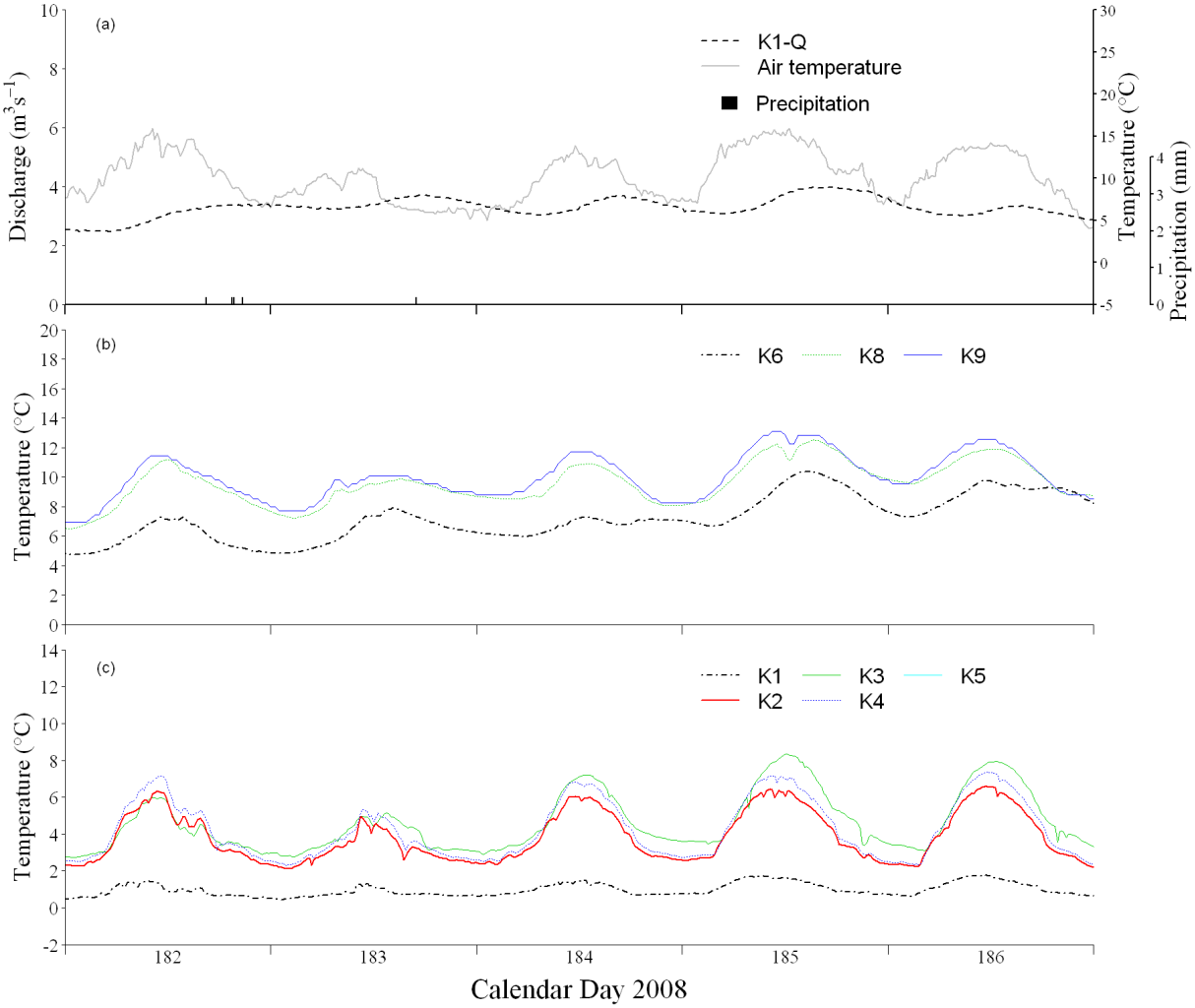

Figure 5.11 - Period 1 Day 182-186: Early summer, warm, high flows: Hydro-climatological and water temperature variation during Period 1 (day 182-186 in 2008). (a) Discharge data from gauging station at K1, precipitation and air temperature from AWS at K1; (b) Near bed water temperature data from K6-K9; (c) Near bed water temperature data from K1-K4.

the thermal increase between the inlet and outlet of the second lake can be estimated at ~2.2°C. This increase is equivalent to that observed during the other periods. This may simply be due to the second lakes position within the catchment and the surrounding valley which is much less confined allowing greater atmospheric exposure and hence earlier warming. Correlation and cross correlation coefficients of water temperature and air temperature

illustrate the contrasting thermal responses between sites. K6 has a ccf of 0.56 ($p<0.001$) and a lag of 3.5hrs, all the other sites have ccf >0.73 ($p<0.001$) with lags between 0 and 1.5hrs.

Period 2) ***Day 203-207: Mid season, moderate air temperature, precipitation dominated.***

Rainfall was recorded every day at the upper valley sites during Period 2 but confined to days 204 and 207 in the lower valley. In comparison to other recorded rainfall events, these were long duration, one spanning the whole of day 204 (Figure 5.12; Tables 5.8 and 5.10). This prolonged rainfall event dominated the hydrograph with the highest discharge recorded for all gauging stations associated with this event (K1 = 4.41 m^3s^{-1}, K2 = 5.51 m^3s^{-1}, K8 = 9.99 m^3s^{-1}). During this precipitation dominated section of the flow regime maximum discharge at K2 exceeded that recorded at K1, and averages were almost equivalent (K1 = 3.58 m^3s^{-1}, K2 = 3.50 m^3s^{-1}).

Average air temperatures ranged from 8.04°C at K1 to 10.43°C close to K4 but thermal variability was greatly reduced (SD K1 = 2.24, K4 = 2.82). There was a week diurnal signal within the air temperature record though this completely disappeared on day 204.

Patterns in water column temperature showed a high fidelity to air temperature with low thermal variation and a very weak diurnal temperature signal. Correlation coefficients for most sites remain high ($r =>0.85$) with lags ranging from 15 min to 2 hrs. However for K3 ccf = 0.61, the lowest during any highlighted period and for a time on day 207 the water temperature within this tributary drops below that of the main channel. This response to the second rainfall event is contrary to patterns observed at all other sites which warm or stay

constant. Therefore it may be a result of some event local to K3 such as the avalanching of the snowpack into the main stream, perhaps triggered by the rainwater. The overall impact of the second rainfall event was convergence of water temperature at K2-K5. Longitudinal patterns in air-water correlation show a decrease from K1 to K6 along the main channel; however, K3 (i.e. snowmelt tributary) has a correlation coefficient of 0.59 and K4 below its confluence has a coefficient of 0.93. Below the lakes correlation coefficients increase with distance. Thermal patterns across the braids are similar to those recorded longitudinally with a reduced diurnal signal, which disappears on day 204. CCF at all lateral sites are high (>0.85) with water temperature at most peaking within an hour of local air temperature. The exception is B9; the probable groundwater seep which has a lag of 3.5hrs.

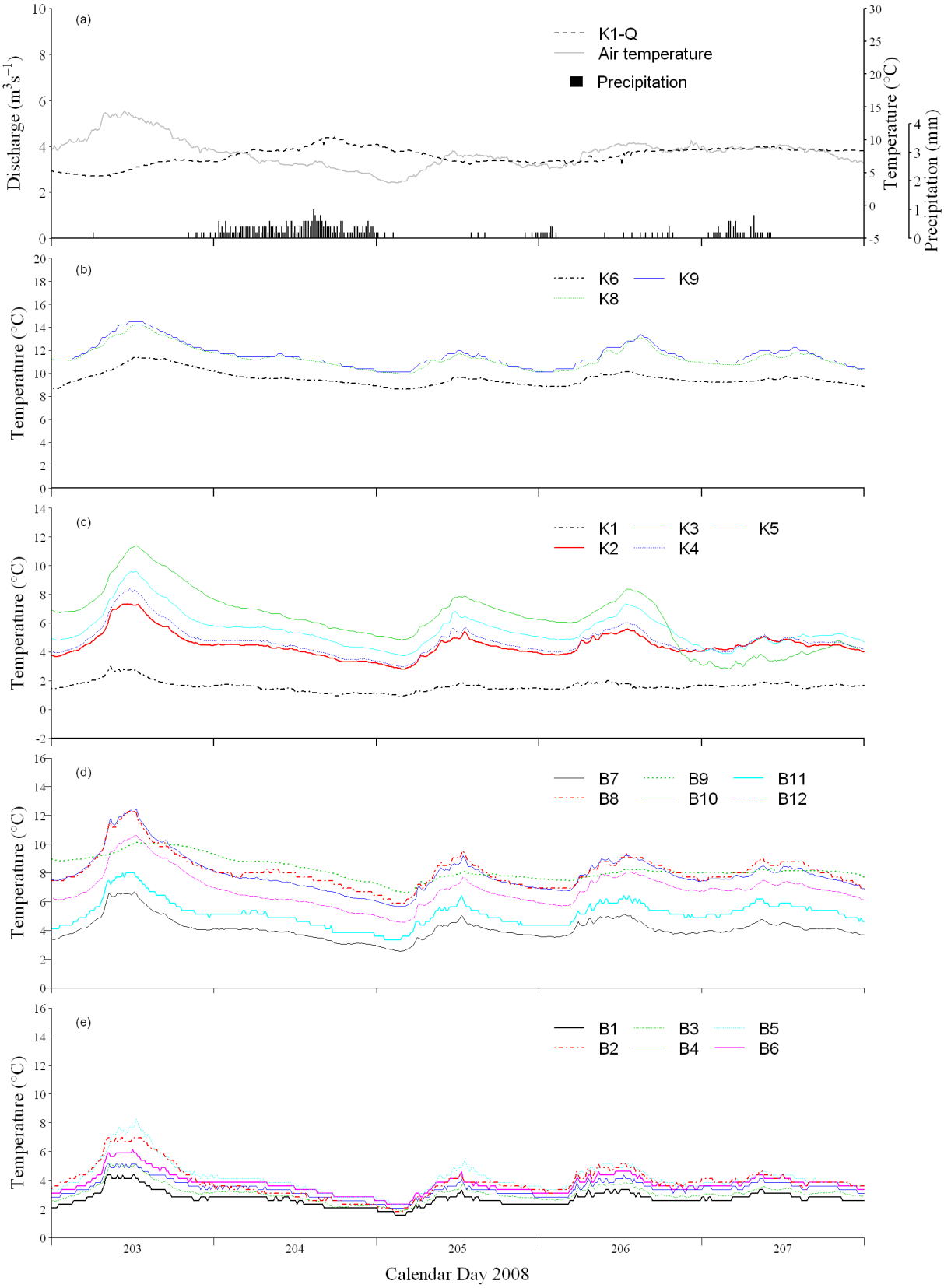

Figure 5.12- Period 2 Day 203-207: Mid season, moderate air temperature, precipitation dominated. Hydro-climatological and water temperature variation during Period 2 (day 203-207 in 2008). (a) Discharge data from gauging station at K1, precipitation and air temperature from AWS at K1; (b) Near bed water temperature data from K6-K9; (c) Near bed water temperature data from K1-K4; (d) Near bed water temperature data from B7-B12; (e) Near bed water temperature data from B1-B6.

Period 3) ***Day 208 to 212: Mid-season, dry with high air temperature***

This period included the maximum recorded air temperature in 2008 of 27.87°C on day 210 (Figure 5.13 and Tables 5.8 and 5.10). Discharge is above average but follows a diurnal pattern with flows peaking a few hours after air temperatures. The exception is day 208 (and day 209 at site K8) which includes the falling limb of the second rainfall event of period 2. All sites except K6 achieve their highest average water temperature within this period ranging from 2.29°C at K1 to 12.99°C at K9. Air-water Correlation coefficients remain high (>0.75) at all sites. Sites K4 to K9 record seasonal maximum water temperatures during this period.

The pattern of lateral variation within the upper braids illustrates the response of different water sources to high air temperatures. All sites have high air-water correlation and cross correlation coefficients (B9 = 0.84, B1-B8 and B10-B12> 0.90) and record highest average temperatures but the timing and extent of peak temperatures varies. Water temperature at sites along the main glacial channel peak near synchronously with local air temperature; capped by the increase in coldwater input. In contrast, temperatures in most other channels lag behind air temperature. All non-glacial channel fed record their maximum water temperature within this period (Table 5.8). K2 situated in a channel with a north facing snowmelt source displays a pattern intermediate between the glacial and south facing snowmelt channels, peaking before air temperature but also recording its seasonal maxima of 9.84°C.

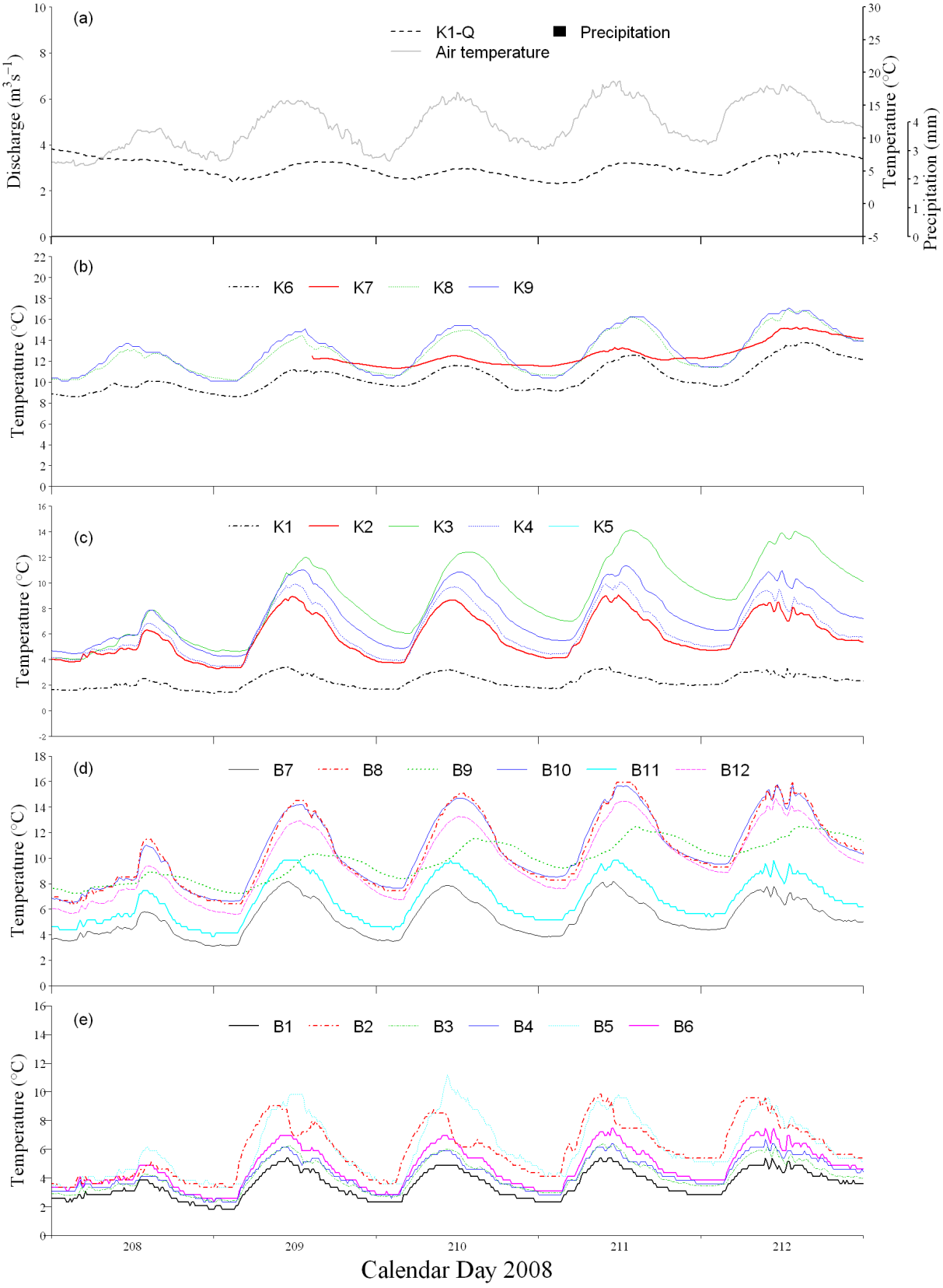

Figure 5.13 - Period 3 day 208 to 212: Mid-season, dry with high air temperature. Hydro-climatological and water temperature variation during Period 3 (day 208-212 in 2008). (a) Discharge data from gauging station at K1, precipitation and air temperature from AWS at K1; (b) Near bed water temperature data from K6-K9; (c) Near bed water temperature data from K1-K4; (d) Near bed water temperature data from B7-B12; (e) Near bed water temperature data from B1-B6.

Period 4) ***Day 214 to 218: Mid-season, dry with low air temperatures***

Air temperatures remained relatively low, not exceeding 20.27°C at K4 with daily averages of 6.53°C and 9.18°C at K1 and K4 respectively (Figure 5.14 and Tables 5.8 and 5.10). Discharge also remained low averaging 1.70m^3s^{-1}, 1.19m^3s^{-1} and 4.33m^3s^{-1} at K1, K2 and K8 respectively. Sites K1, K2 and K4 record their seasonal water temperature maxima during this period (K1 = 4.41°C K2 = 9.77°C and K4 = 10.57°C) as the interaction between melt water generation and water column warming appears shifted from Period 3. As a result the greater thermal variability of glacial sourced headwater channels is also seen during this period. Longitudinal patterns of thermal increase change, as this is the first period when gradual warming with distance from K1 peaks at K8 before dropping to K9. This is also the first period to have a full record from K7 and illustrates the markedly dampened diurnal temperature cycle at the outlet of the second lake. K7 displays the least variable temperature record of any site during this period (SD = 0.66) with an average temperature of 11.98°C only exceeded at K8. Within the braids glacial dominated channels reach their seasonal maxima but averages of all channels are reduced relative to Period 3. Air-water correlation coefficients reduce at all sites relative to Period 3 (though still remain quite high at >0.78), except B9 which increases to 0.76. There is a shift in timing of daily water temperature maxima with all channels except B9 peaking before the local air temperature.

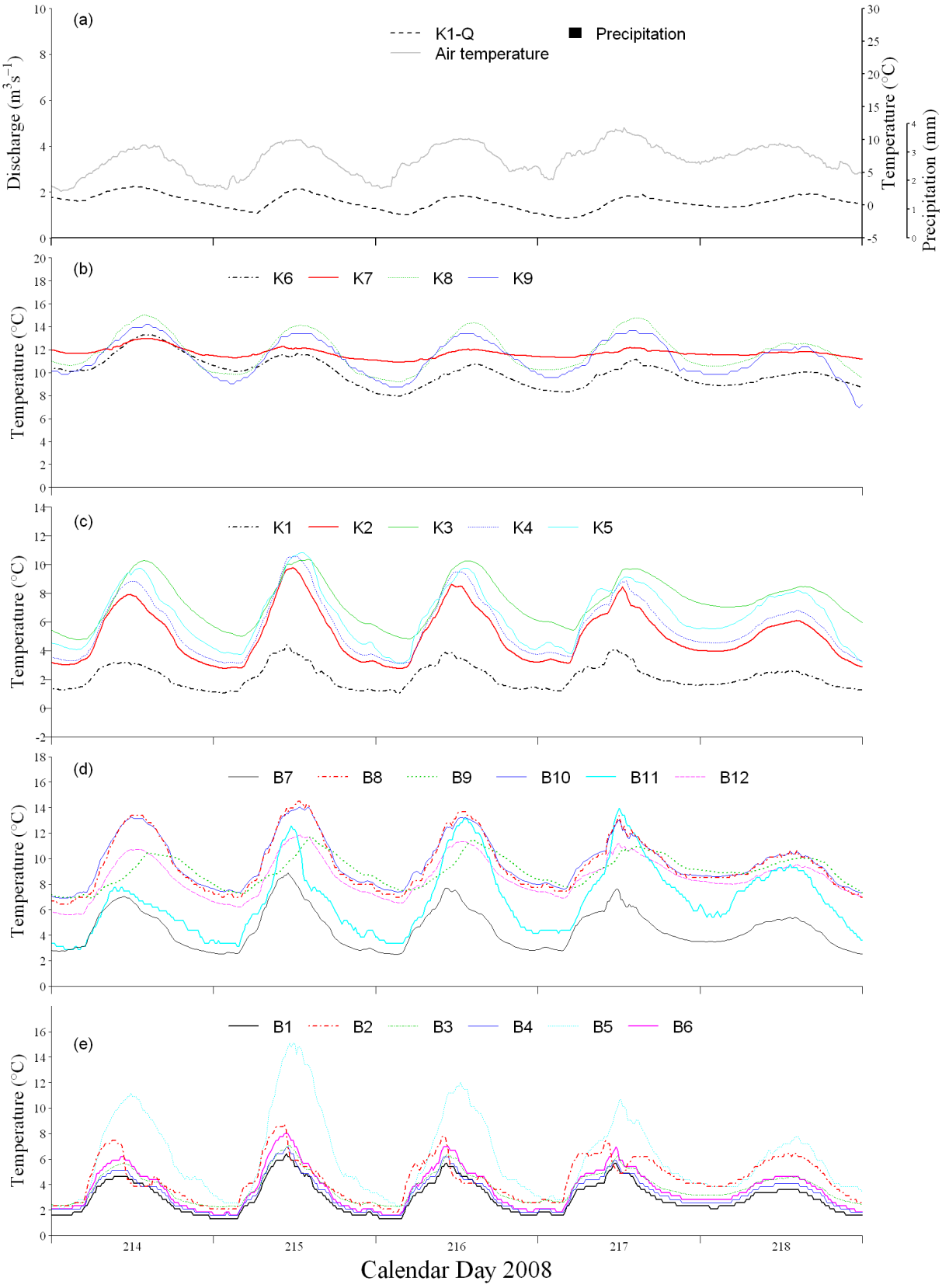

Figure 5.14 - Period 4 day 214 to 218: Mid-season, dry with low air temperatures. Hydro-climatological and water temperature variation during Period 4 (day 214-218 in 2008). (a) Discharge data from gauging station at K1, precipitation and air temperature from AWS at K1; (b) Near bed water temperature data from K6-K9; (c) Near bed water temperature data from K1-K4; (d) Near bed water temperature data from B7-B12; (e) Near bed water temperature data from B1-B6.

Period 5) ***Day 238 to 242: Late season, cool and wet***

Average air temperature is 6.29°C and 7.48°C at K1 and K4 respectively making this the coldest period selected (Figure 5.15 and Tables 5.9 and 5.11). The amplitude of diurnal patterns is reduced by precipitation events on day 239, 241 and 242 but is still discernible. Discharge at all sites is the lowest of any selected period as late in the season falling air temperatures correspond with a reduction in meltwater production. There are discharge peaks associated with the rainfall events in the upper basin but these are small and not transmitted to K8. Water temperature during this period is relatively cool with patterns closely correlated with those of local air temperature (CCF>0.79, lags from 0 to 1.5 hrs). Lowest thermal variability is observed at K7 followed by K1. During periods one to four the thermal pattern recorded at B11 was intermediate between other sites along the main glacial channel and B12 a snowmelt channel. By period five there has been a reduction in lateral connectivity (evidenced by field observations) resulting in the thermal pattern at B11 shifting from that of a channel with mixed water sources to that of a channel sourced purely from glacial melt. Lateral thermal variation as a whole is reduced as thermal patterns within different but similarly sourced channels coalesce.

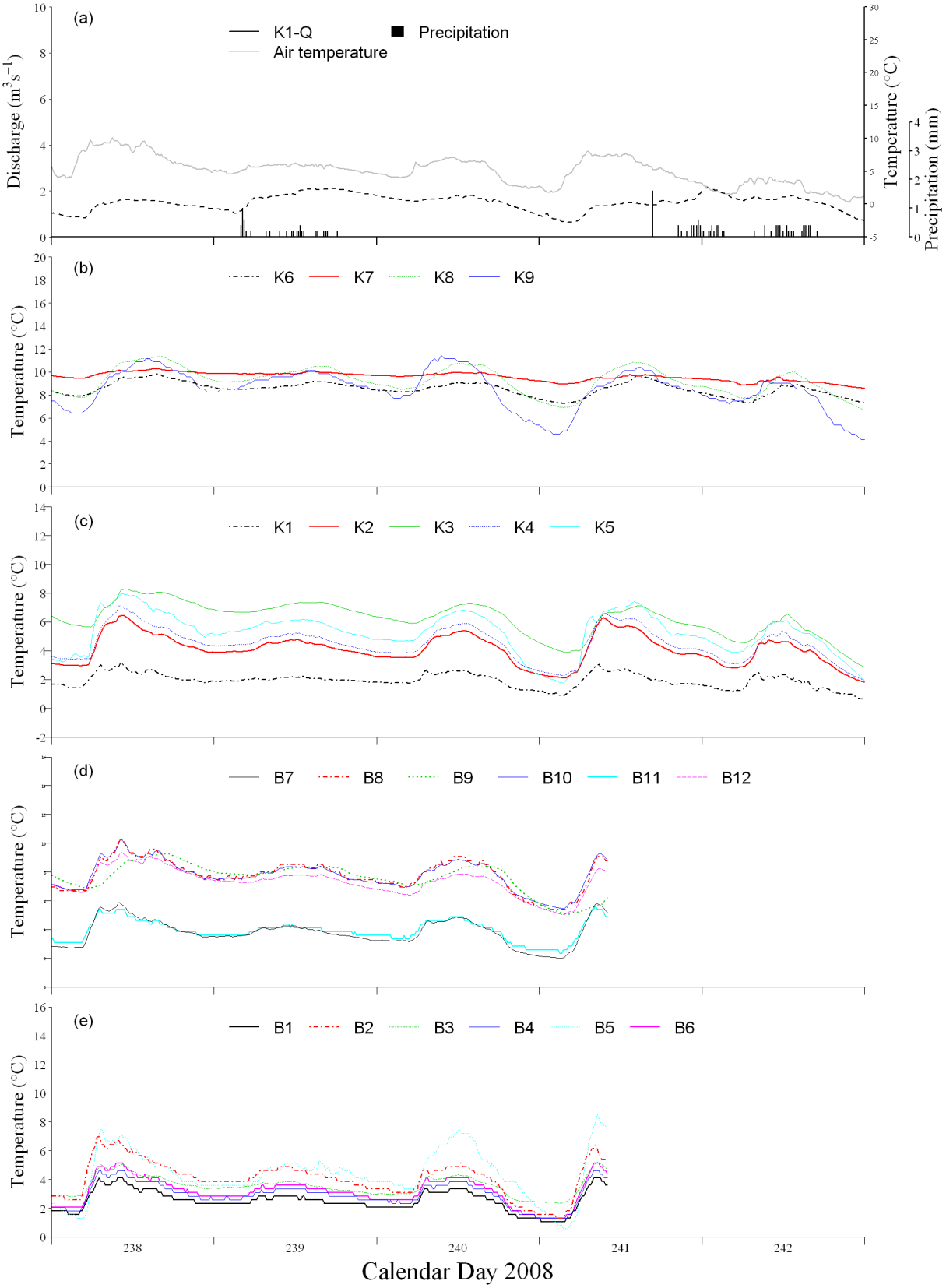

Figure 5.15 - Period 5 Day 238 to 242: Late season, cool and wet. Hydro-climatological and water temperature variation during Period 5 (day 238-242 in 2008). (a) Discharge data from gauging station at K1, precipitation and air temperature from AWS at K1; (b) Near bed water temperature data from K6-K9; (c) Near bed water temperature data from K1-K4; (d) Near bed water temperature data from B7-B12; (e) Near bed water temperature data from B1-B6.

Period 6) ***Day 196-200: Early summer, moderate air temperature, long duration rainfall event***

Air temperature within this period was highly variable ranging from 2.45°C to 22.07°C but was constant and low during the rainfall event which stretched from day 197 to 199 (Figure 5.16 and Tables 5.9 and 5.11). Discharges are high, averaging at 2.33m^3s^{-1}, 3.16m^3s^{-1} and 9.43m^3s^{-1} at K1, K2, and K8 respectively. There is a general pattern of reduced amplitude diurnal streamflow at K1 and K2 which is interrupted by a rainfall event. Discharge patterns at B1 and B12 follows the same trend. The diurnal pattern in water column thermal variability is retained at all sites; however the prolonged rainfall event dampens this. Thermal variability at K1 is greatly reduced (SD=0.41) relative to that of other sites longitudinally with temperatures not exceeding 2.40°C. Highest average temperatures in the braids were recorded at B13 (8.99°C) a groundwater stream which also showed the lowest air-water temperature correlation (0.65).

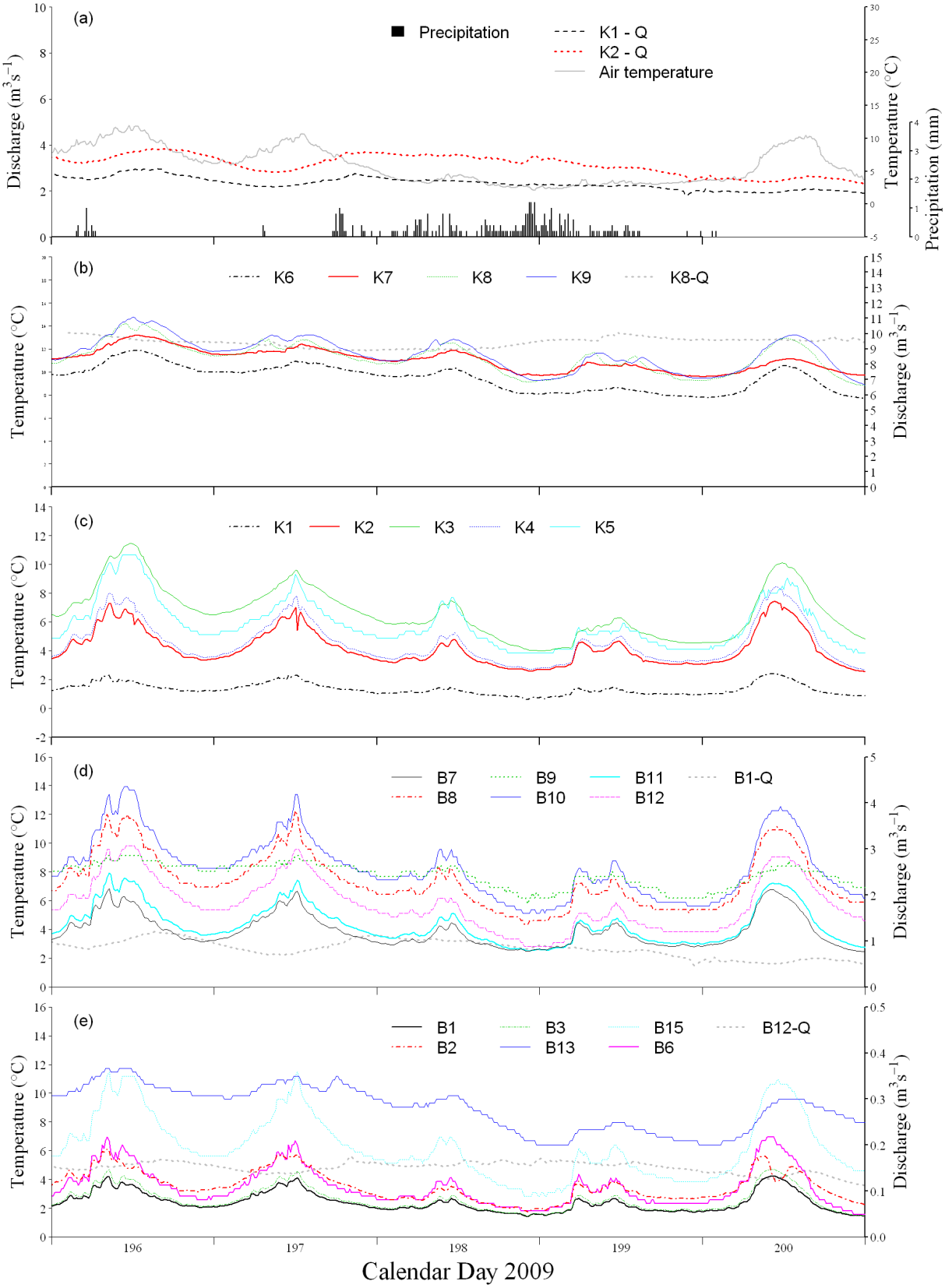

Figure 5.16 - Period 6 Day 196-200: Early summer, moderate air temperature, long duration rainfall event. Hydro-climatological and water temperature variation during Period 6 (day 196-200 in 2009), (a) Discharge data from gauging stations at K1 and K2, precipitation and air temperature from AWS at K1; (b) Near bed water temperature data from K6-K9, Discharge data from gauging station at K8; (c) Near bed water temperature data from K1-K5; (d) Near bed water temperature data from B7-B12, discharge data from gauging station at B1; (e) Near bed water temperature data from B1-B3, B6, B13 and B15, discharge data from gauging station at B12.

Period 7) ***Day 235-240: Late summer, average temperature, reducing flows***

Hydrograph patterns within this period reflect the reducing meltwater input. Discharge at K8 is reducing and discharge at K2 drops to values similar to those at K1 (Figure 5.17 and Tables 5.9 and 5.11). Thermal patterns shift too. K6 displays a relatively high thermal range and variability but this is not transmitted to K7 which has the lowest thermal variation of any longitudinal site. Air-water correlation coefficients of K6-K9 are high compared to other periods. This shift may be due to an interaction of reduced flows, shifting dominance of water source and specific bathymetric details relating to which areas of channels run dry.

Period 8) ***Day 235-240: Late summer, average temperature, reducing flows***

Hydrograph patterns within this period reflect the reducing meltwater input. Discharge at K8 is reducing and discharge at K2 drops to values similar to those at K1 (Figure 5.18 and Tables 5.9 and 5.11). Thermal patterns shift too. K6 displays a relatively high thermal range and variability but this is not transmitted to K7 which has the lowest thermal variation of any longitudinal site. Air-water correlation coefficients of K6-K9 are high compared to other periods. This shift may be due to an interaction of reduced flows, shifting dominance of water source and specific bathymetric details relating to which areas of channels run dry.

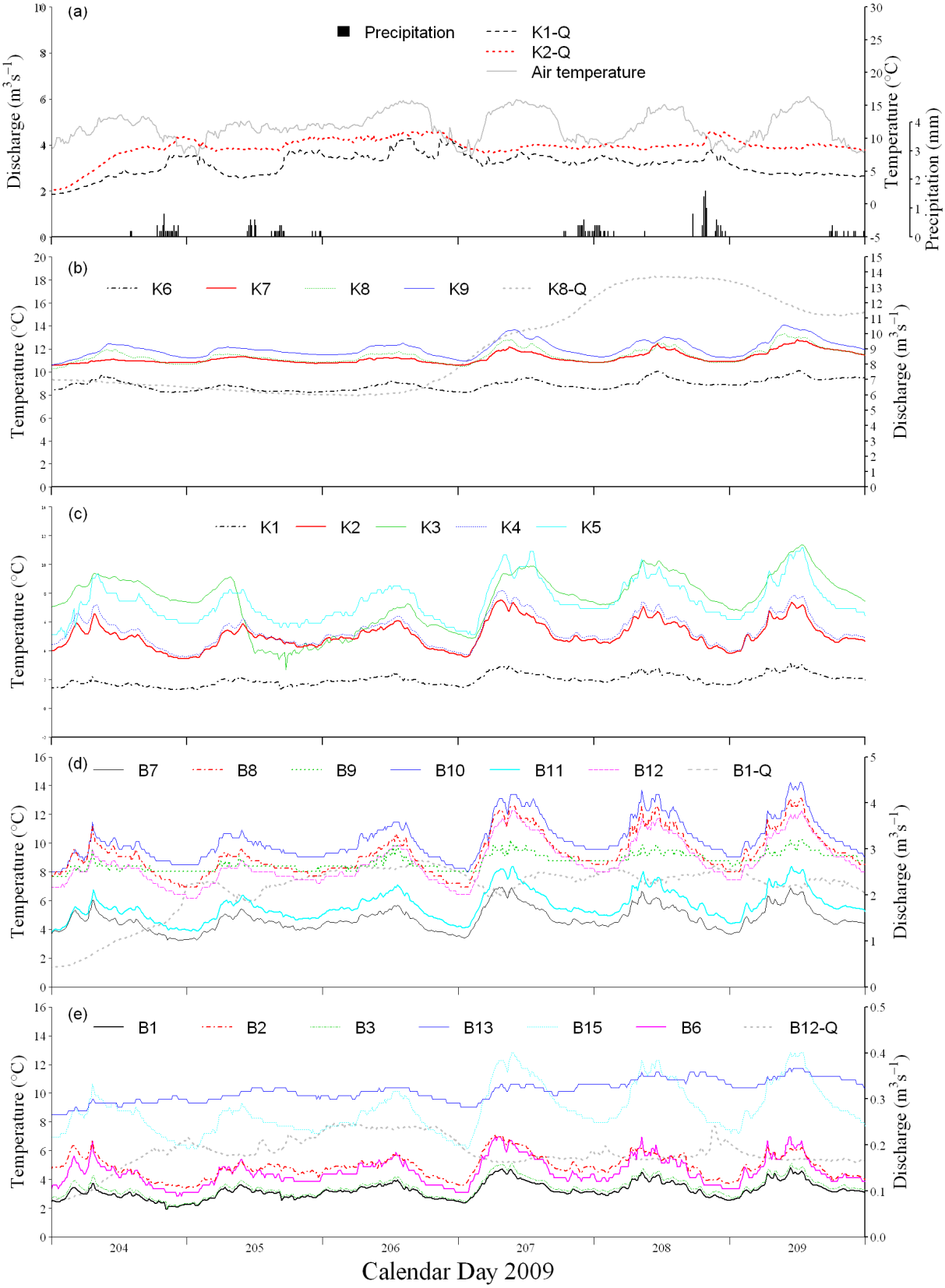

Figure 5.17 - Period 7 Day 204-209: Mid-season, high air temperature, high discharge. Hydro-climatological and water temperature variation during Period 7 (day 204-209 in 2009), (a) Discharge data from gauging stations at K1 and K2, precipitation and air temperature from AWS at K1; (b) Near bed water temperature data from K6-K9, Discharge data from gauging station at K8; (c) Near bed water temperature data from K1-K5; (d) Near bed water temperature data from B7-B12, discharge data from gauging station at B1; (e) Near bed water temperature data from B1-B3, B6, B13 and B15, discharge data from gauging station at B12.

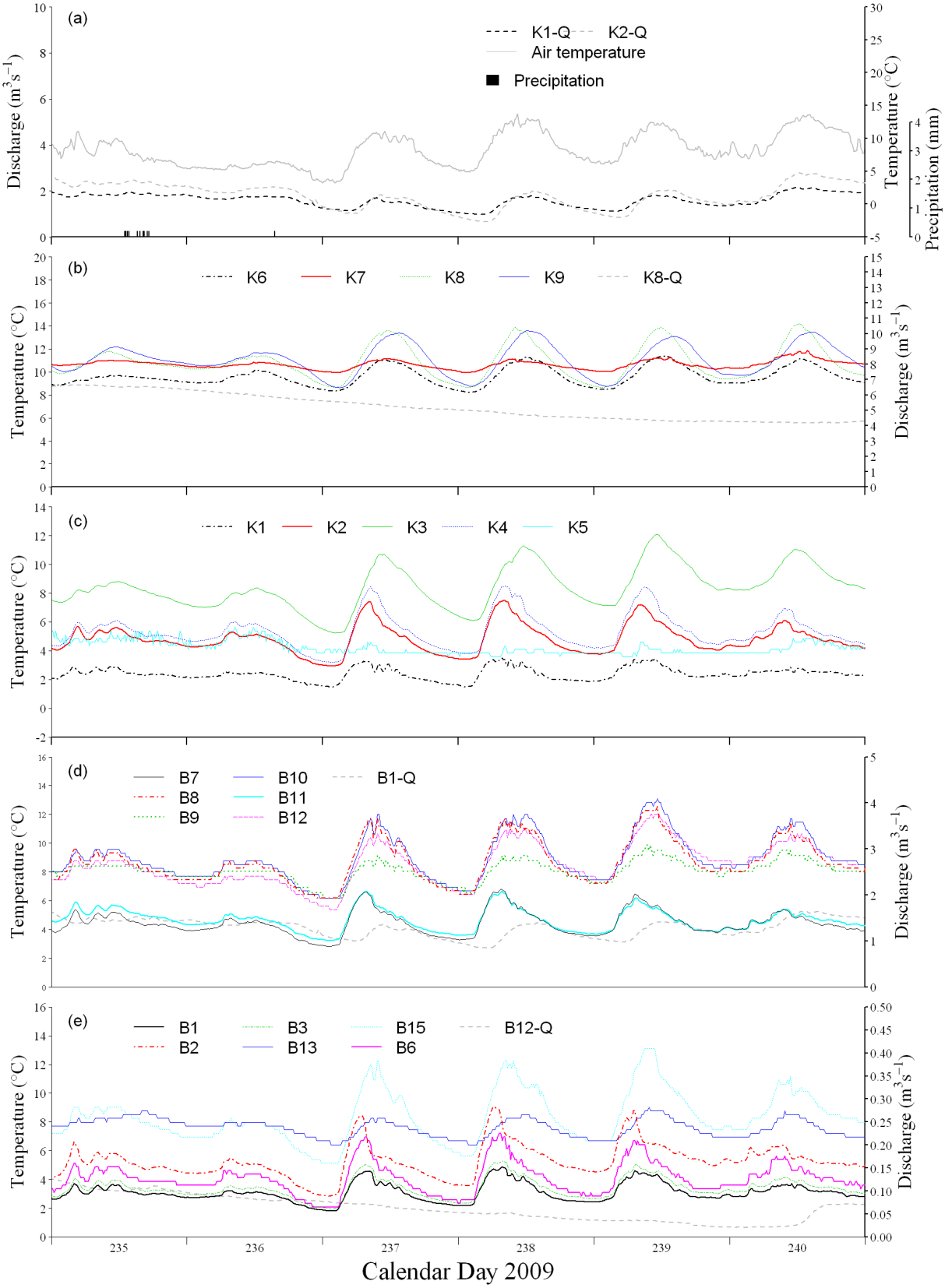

Figure 5.18 - Period 8 Day 235-240: Late summer, average temperature, reducing flows. Hydro-climatological and water temperature variation during Period 8 (day 235-240 in 2009), (a) Discharge data from gauging stations at K1 and K2, precipitation and air temperature from AWS at K1; (b) Near bed water temperature data from K6-K9, Discharge data from gauging station at K8; (c) Near bed water temperature data from K1-K5; (d) Near bed water temperature data from B7-B12, discharge data from gauging station at B1; (e) Near bed water temperature data from B1-B3, B6, B13 and B15, discharge data from gauging station at B12.

Table 5.8 - Descriptive statistics for near bed water temperatures at sites longitudinally within the Kårsavagge for Periods 1 to 4 (all in 2008). Discharge data from gauging stations at K1, K2 and K5 also included. SD =standard deviation, Cor = Correlation with air temperature, CCF = cross correlation factor (max correlation with air temperature taking into account different lag times), lag = time in minutes thermal water patterns lag behind those of air temperature.

		Longitudinal site									Discharge (m^3s^{-1})		
		K1	K2	K3	K4	K5	K6	K7	K8	K9	Q_{K1}	Q_{K2}	Q_{K3}
Period 1 Day 182-186	Mean (°C)	0.98	3.86	4.61	4.25	-	7.19	-	9.59	10.02	3.29	2.47	8.52
	Max. (°C)	1.78	6.58	8.35	7.36	-	10.37	-	12.51	13.11	4.01	3.32	9.22
	Min. (°C)	0.44	2.12	2.74	2.32	-	4.75	-	6.52	6.95	2.46	1.35	9.22
	SD	0.36	1.36	1.55	1.57	-	1.51	-	1.42	1.52	0.34	0.41	0.67
	Cor.	0.83	0.86	0.87	0.87	-	0.54	-	0.74	0.80	(*)	(*)	0.11
	(r^2)	*(0.68)*	*(0.74)*	*(0.75)*	*(0.76)*		*(0.29)*		*(0.57)*	*(0.63)*	*(*)*	*(*)*	*(0.01)*
	CCF	0.82	0.87	0.88	0.92	-	0.56	-	0.75	0.88			
	lag (min)	*0*	*-30*	*45*	*75*		*75*		*15*	*45*			
Period 2 Day 203-207	Mean (°C)	1.61	4.48	6.35	4.75	5.55	9.55	-	11.38	11.59	3.58	3.50	8.10
	Max. (°C)	3.00	7.35	11.39	8.41	9.60	11.39	-	14.23	14.52	4.41	5.51	9.99
	Min. (°C)	0.87	2.79	2.83	2.96	3.75	8.61	-	9.93	10.11	2.70	2.27	6.16
	SD	0.36	0.87	1.96	1.01	1.20	0.63	-	0.95	1.02	0.37	0.66	1.16
	Cor.	0.88	0.87	0.59	0.93	0.85	0.81	-	0.89	0.91	-0.55	-0.69	-0.53
	(r^2)	*(0.78)*	*(0.73)*	*(0.35)*	*(0.88)*	*(0.73)*	*(0.65)*	-	*(0.80)*	*(0.83)*	*(0.31)*	*(0.47)*	*(0.28)*
	CCF	0.89	0.88	0.61	0.93	0.87	0.86	-	0.92	0.92			
	lag (min)	*45*	*-45*	*-75*	*-15*	*-45*	*-120*		*-60*	*-45*			
Period 3 Day 208-212	Mean (°C)	2.29	5.82	8.88	6.32	7.43	10.44	12.61	12.75	12.99	3.02	2.82	6.50
	Max. (°C)	3.42	9.03	14.12	10.09	11.32	13.75	15.22	17.00	17.13	3.81	3.71	9.32
	Min. (°C)	1.35	3.28	4.03	3.47	4.25	8.57	11.30	10.17	10.11	2.31	1.96	5.54
	SD	0.54	1.67	2.96	1.95	2.10	1.35	1.11	1.88	2.01	0.39	0.47	1.03
	Cor.	0.92	0.92	0.83	0.91	0.94	0.75	0.42	0.86	0.88	0.13	-0.10	-0.35
	(r^2)	*(0.86)*	*(0.85)*	*(0.69)*	*(0.83)*	*(0.88)*	*(0.57)*	*(0.18)*	*(0.74)*	*(0.77)*	*0.02*	*0.01*	*0.13*
	CCF	0.93	0.93	0.83	0.95	0.95	0.75		0.86	0.88			
	lag (min)	*15*	*-30*	*-15*	*60*	*15*	*0*		*15*	*30*			
Period 4 Day 214-218	Mean (°C)	2.25	5.12	7.42	5.71	6.46	10.53	11.98	12.15	11.69	1.70	1.19	4.35
	Max. (°C)	4.41	9.77	10.38	10.57	10.86	13.30	13.50	15.03	14.24	2.50	2.31	6.00
	Min. (°C)	1.05	2.75	4.75	3.12	3.15	7.96	10.89	9.20	8.78	0.84	0.48	3.33
	SD	0.85	1.85	1.71	2.02	1.98	1.34	0.66	1.64	1.54	0.43	0.46	0.80
	Cor.	0.79	0.86	0.91	0.94	0.95	0.49	0.39	0.85	0.86	0.14	(*)	(*)
	(r^2)	*(0.63)*	*(0.74)*	*(0.83)*	*(0.88)*	*(0.89)*	*(0.24)*	*(0.15)*	*(0.72)*	*(0.73)*	*(0.14)*		
	CCF	0.82	0.88	0.95	0.95	0.95	0.51	0.41	0.87	0.87			
	lag (min)	*60*	*0*	*-60*	*15*	*0*	*-60*	*-60*	*-45*	*-30*			

Table 5.9 - Descriptive statistics for near bed water temperatures at sites longitudinally within the Kårsavagge for Periods 5 to 8 (nb Period 5 in 2008, Periods 6-8 in 2009). Discharge data from gauging stations at K1, K2 and K5 also included. SD =standard deviation, Cor = Correlation with air temperature, CCF = cross correlation factor (max correlation with air temperature taking into account different lag times), lag = time in minutes thermal water patterns lag behind those of air temperature.

		Longitudinal site									Discharge (m^3s^{-1})		
		K1	K2	K3	K4	K5	K6	K7	K8	K9	Q_{K1}	Q_{K2}	Q_{K3}
Period 5 Day 238-242	Mean (°C)	2.07	4.32	6.79	4.77	5.51	8.79	9.78	9.68	9.06	1.50	1.07	3.22
	Max. (°C)	3.52	7.87	10.80	8.87	9.64	11.11	10.67	13.85	13.11	2.13	1.78	3.48
	Min. (°C)	0.90	2.10	3.88	2.28	1.73	7.26	8.94	6.92	4.63	0.63	0.46	3.22
	SD	0.52	1.15	1.30	1.27	1.58	0.77	0.33	1.44	1.77	0.35	0.35	0.05
	Cor.	0.84	0.79	0.90	0.95	0.93	0.87	0.83	0.92	0.90	0.19	0.03	-0.04
	(r^2)	*(0.70)*	*(0.62)*	*(0.80)*	*(0.90)*	*(0.87)*	*(0.75)*	*(0.70)*	*(0.85)*	*(0.81)*	*(0.04)*	*(*)*	*(*)*
	CCF	0.83	0.80	0.92	0.95	0.93	0.92	0.84	0.95	0.90			
	lag (min)	*0*	*-45*	*-60*	*-15*	*0*	*-90*	*-15*	*-60*	*0*			
Period 6 Day 196-200	Mean (°C)	1.34	4.18	6.71	4.57	5.89	9.49	11.06	11.25	11.61	2.33	3.16	9.43
	Max. (°C)	2.40	7.43	11.47	8.43	10.65	11.88	13.19	14.21	14.79	2.96	3.83	10.07
	Min. (°C)	0.60	2.58	3.99	2.72	3.86	7.77	9.59	8.89	9.08	1.80	2.37	8.91
	SD	0.41	1.23	1.81	1.44	1.65	1.12	0.94	1.29	1.37	0.26	0.42	0.32
	Cor.	0.87	0.88	0.90	0.89	0.86	0.73	0.60	0.77	0.76	0.16	-0.10	0.15
	(r^2)	*(0.75)*	*(0.77)*	*(0.80)*	*(0.79)*	*(0.86)*	*(0.53)*	*(0.36)*	*(0.60)*	*(0.58)*	*(0.02)*	*(-0.01)*	*(0.02)*
	CCF	0.89	0.88	0.86	0.89	0.86	0.74	0.62	0.78	0.78			
	lag (min)	*53*	*15*	*-15*	*15*	*0*	*-38*	*-83*	*-30*	*-75*			
Period 7 Day 204-209	Mean (°C)	1.98	5.09	7.52	5.40	7.42	8.87	11.21	11.41	12.03	3.15	3.91	9.13
	Max. (°C)	3.13	7.52	11.35	8.24	11.19	10.11	12.79	13.31	14.08	4.28	4.60	13.75
	Min. (°C)	1.26	3.43	2.67	3.59	4.88	8.22	10.57	10.18	10.62	1.82	2.02	6.00
	SD	0.38	0.93	1.86	1.06	1.37	0.46	0.49	0.64	0.72	0.49	0.48	2.94
	Cor.	0.87	0.87	0.54	0.90	0.90	0.66	0.65	0.79	0.80	-0.01	-0.02	0.07
	(r^2)	*(0.75)*	*(0.75)*	*(0.30)*	*(0.81)*	*(0.81)*	*(0.43)*	*(0.43)*	*(0.63)*	*(0.63)*	*(0.00)*	*(0.00)*	*(0.00)*
	CCF	0.89	0.88	0.55	0.90	0.90	0.66	0.65	0.79	0.80			
	lag (min)	*53*	*30*	*-23*	*0*	*0*	*0*	*-8*	*0*	*-30*			
Period 8 Day 235-240	Mean (°C)	2.39	4.81	8.42	5.35	4.25	9.61	10.64	10.84	11.07	1.59	1.79	5.20
	Max. (°C)	3.48	7.49	12.10	8.53	5.91	11.40	11.87	14.16	13.59	2.15	2.78	6.65
	Min. (°C)	1.47	2.93	5.25	3.20	3.61	8.22	9.93	8.65	8.65	0.97	0.66	4.17
	SD	0.44	0.98	1.49	1.18	0.49	0.81	0.37	1.44	1.32	0.29	0.54	0.86
	Cor.	0.73	0.79	0.91	0.83	0.15	0.91	0.88	0.93	0.79	0.60	0.46	-0.21
	(r^2)	*(0.54)*	*(0.62)*	*(0.83)*	*(0.68)*	*(0.02)*	*(0.83)*	*(0.77)*	*(0.87)*	*(0.79)*	*0.36*	*0.21*	*-0.04*
	CCF	0.88	0.89	0.92	0.90	0.17	0.94	0.88	0.94	0.93			
	lag (min)	*120*	*105*	*-30*	*90*	*-60*	*-60*	*-23*	*-30*	*-120*			

Table 5.10 - Descriptive statistics for near bed water temperatures at sites laterally (from the upper braided section) within the Kårsavagge for Periods 2 to 5 (all in 2008). SD =standard deviation, Cor = Correlation with air temperature, CCF = cross correlation factor (max correlation with air temperature taking into account different lag times), lag = time in minutes thermal water patterns lag behind those of air temperature.

		Sites within the braided section											
		B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
Period 2	Mean (°C)	2.72	3.89	3.11	4.15	3.43	3.76	4.13	8.14	8.29	7.97	5.18	6.85
Day 203-	Max. (°C)	4.37	6.95	5.20	8.25	5.14	6.17	6.71	12.28	10.14	12.45	7.99	10.65
207	Min. (°C)	1.58	1.83	1.86	2.34	2.08	2.34	2.54	5.91	6.60	5.66	3.35	4.58
	SD	0.50	1.07	0.61	1.06	0.61	0.71	0.77	1.18	0.79	1.30	0.91	1.18
	Cor.	0.85	0.94	0.89	0.89	0.89	0.89	0.88	0.90	0.81	0.93	0.86	0.92
	(r^2)	*(0.73)*	*(0.88)*	*(0.79)*	*(0.79)*	*(0.79)*	*(0.79)*	*(0.78)*	*(0.80)*	*(0.65)*	*(0.87)*	*(0.75)*	*(0.84)*
	CCF	0.85	0.94	0.89	0.89	0.89	0.89	0.88	0.90	0.87	0.94	0.87	0.93
	lag (min)	*-15*	*0*	*-15*	*-30*	*-30*	*-15*	*-15*	*-30*	*-210*	*-30*	*-30*	*-60*
Period 3	Mean (°C)	3.52	5.97	4.14	6.14	4.27	4.72	5.37	10.59	9.80	10.68	6.72	9.76
Day 208-	Max. (°C)	5.40	9.84	6.38	11.19	6.69	7.47	8.20	15.95	12.53	15.76	9.84	14.66
212	Min. (°C)	1.83	3.35	2.34	3.35	2.34	2.34	3.10	6.43	7.23	6.53	3.86	5.62
	SD	0.98	1.84	1.11	2.05	1.12	1.37	1.45	2.82	1.55	2.72	1.75	2.60
	Cor.	0.92	0.88	0.93	0.92	0.93	0.93	0.94	0.93	0.66	0.96	0.95	0.94
	(r^2)	*(0.84)*	*(0.78)*	*(0.87)*	*(0.85)*	*(0.86)*	*(0.86)*	*(0.88)*	*(0.87)*	*(0.44)*	*(0.92)*	*(0.90)*	*(0.88)*
	CCF	0.92	0.90	0.93	0.93	0.93	0.93	0.94	0.94	0.84	0.96	0.95	0.95
	lag (min)	*15*	*30*	*0*	*15*	*0*	*15*	*15*	*-60*	*-270*	*-30*	*0*	*-45*
Period 4	Mean (°C)	2.98	4.24	3.78	6.20	3.33	3.72	4.57	9.70	9.03	9.86	6.40	8.46
Day 214-	Max. (°C)	6.43	8.78	7.08	15.09	6.95	7.99	8.87	14.52	11.74	14.06	13.95	11.86
218	Min. (°C)	1.33	1.83	2.24	2.08	1.58	1.58	2.49	6.43	6.92	6.92	2.84	5.59
	SD	1.27	1.63	1.21	3.18	1.30	1.60	1.61	2.20	1.19	2.01	2.72	1.65
	Cor.	0.80	0.65	0.82	0.77	0.83	0.78	0.81	0.89	0.76	0.89	0.86	0.92
	(r^2)	*(0.63)*	*(0.42)*	*(0.66)*	*(0.59)*	*(0.69)*	*(0.60)*	*(0.65)*	*(0.80)*	*(0.58)*	*(0.80)*	*(0.75)*	*(0.86)*
	CCF	0.88	0.77	0.88	0.86	0.84	0.86	0.87	0.89	0.92	0.89	0.87	0.93
	lag (min)	*105*	*165*	*105*	*120*	*30*	*120*	*90*	*15*	*-135*	*15*	*15*	*0*
Period 5	Mean (°C)	2.80	4.24	3.76	4.49	3.14	3.37	4.00	7.91	7.61	7.96	4.11	7.49
Day 238-	Max. (°C)	5.65	7.99	6.01	9.05	5.40	6.17	6.88	12.56	10.57	12.44	6.69	11.09
242	Min. (°C)	1.07	1.33	2.35	0.57	1.33	1.33	1.98	4.63	4.69	4.81	2.34	5.02
	SD	0.98	1.26	0.82	1.77	0.95	1.06	1.02	1.55	1.23	1.46	0.84	1.25
	Cor.	0.46	0.83	0.65	0.55	0.74	0.58	0.56	0.86	0.63	0.88	0.70	0.86
	(r^2)	*(0.21)*	*(0.70)*	*(0.42)*	*(0.30)*	*(0.55)*	*(0.34)*	*(0.31)*	*(0.74)*	*(0.40)*	*(0.77)*	*(0.49)*	*(0.74)*
	CCF	0.46	0.84	0.65	0.55	0.74	0.59	0.56	0.86	0.73	0.88	0.70	0.87
	lag (min)	*0*	*15*	*0*	*0*	*-15*	*15*	*15*	*-15*	*-150*	*-15*	*15*	*-30*

Table 5.11 - Descriptive statistics for near bed water temperatures at sites laterally (from the upper braided section) within the Kårsavagge for Periods 5 to 8 (all in 2009). Discharge data from gauging stations at B1 and B12 also included. SD =standard deviation, Cor = Correlation with air temperature, CCF = cross correlation factor (max correlation with air temperature taking into account different lag times), lag = time in minutes thermal water patterns lag behind those of air temperature.

		Site within the braided section												Discharge (m^3s^{-1})	
		B1	B2	B3	B6	B7	B8	B9	B10	B11	B12	B13	B15	Q_{B1}	Q_{B12}
Period 6 Day 195-200	Mean (°C)	2.43	3.54	2.61	3.49	3.91	7.39	7.78	8.37	4.36	5.82	8.99	6.30	0.84	0.15
	Max. (°C)	4.23	6.11	4.71	6.95	6.83	12.28	9.14	13.95	7.93	9.84	11.74	11.46	1.20	0.18
	Min. (°C)	1.42	1.76	1.46	1.58	2.50	4.37	5.79	5.14	2.50	2.84	6.43	2.84	0.47	0.12
	SD	0.70	1.01	0.81	1.30	1.12	1.87	0.83	2.10	1.33	1.79	1.54	2.17	0.19	0.01
	Cor.	0.86	0.83	0.87	0.85	0.87	0.90	0.71	0.89	0.89	0.89	0.65	0.91		
	(r^2)	*(0.75)*	*(0.69)*	*(0.75)*	*(0.72)*	*(0.75)*	*(0.80)*	*(0.51)*	*(0.79)*	*(0.78)*	*(0.80)*	*(0.42)*	*(0.82)*		
	CCF	0.87	0.84	0.87	0.86	0.87	0.90	0.72	0.89	0.89	0.90	0.67	0.91		
	lag (min)	*45*	*38*	*38*	*53*	*30*	*15*	*-38*	*0*	*0*	*-15*	*98*	*0*		
Period 7 Day 204-209	Mean (°C)	3.32	4.92	3.45	4.54	4.75	9.27	8.71	10.25	5.65	8.70	10.17	8.88	2.13	0.18
	Max. (°C)	4.83	7.06	5.13	6.95	6.95	13.11	10.42	14.24	8.42	12.28	11.74	12.84	2.77	0.24
	Min. (°C)	1.93	3.38	1.96	2.84	3.25	6.95	7.67	7.73	3.78	6.17	8.52	6.17	0.43	0.08
	SD	0.58	0.80	0.64	0.92	0.83	1.44	0.57	1.40	1.04	1.48	0.75	1.62	0.58	0.04
	Cor.	0.79	0.78	0.80	0.85	0.84	0.84	0.65	0.86	0.85	0.82	0.34	0.86		
	(r^2)	*(0.63)*	*(0.61)*	*(0.64)*	*(0.72)*	*(0.70)*	*(0.71)*	*(0.42)*	*(0.73)*	*(0.72)*	*(0.68)*	*(0.12)*	*(0.74)*		
	CCF	0.80	0.82	0.81	0.87	0.85	0.84	0.65	0.86	0.85	0.82	0.34	0.86		
	lag (min)	*38*	*68*	*38*	*53*	*38*	*8*	*0*	*0*	*15*	*0*	*-15*	*0*		
Period 8 Day 235-240	Mean (°C)	3.10	5.28	3.40	4.07	4.45	8.68	8.06	8.94	4.66	8.50	7.61	8.35	1.29	0.06
	Max. (°C)	4.87	9.07	5.28	7.21	6.80	12.56	9.88	13.11	6.65	12.01	9.05	13.11	1.66	0.13
	Min. (°C)	1.81	2.84	1.96	2.08	2.83	6.17	6.17	6.17	3.22	5.40	6.43	5.14	0.84	0.02
	SD	0.64	1.16	0.69	1.07	0.83	1.46	0.72	1.55	0.76	1.41	0.62	1.75	0.19	0.03
	Cor.	0.74	0.55	0.76	0.69	0.73	0.91	0.89	0.94	0.70	0.86	0.78	0.89		
	(r^2)	*(0.55)*	*(0.31)*	*(0.58)*	*(0.48)*	*(0.53)*	*(0.82)*	*(0.79)*	*(0.89)*	*(0.49)*	*(0.75)*	*(0.61)*	*(0.79)*		
	CCF	0.89	0.81	0.89	0.88	0.88	0.93	0.89	0.95	0.84	0.87	0.79	0.92		
	lag (min)	*128*	*173*	*120*	*150*	*135*	*60*	*15*	*15*	*120*	*15*	*-15*	*53*		

5.4. vii) **Winter 2009 temperature**

Over the winter of 2009-2010 the three main channel sites sampled (K1, K4 and K8) all dropped below freezing for a large portion of the logging period. In contrast, temperatures in the pool at A4 remained above freezing for the duration of the winter, recording a minimum temperature of 0.07 °C. The pattern of thermal variation was also different, with high fluctuations in temperature seen at K1, K4 and K8 after day 300, but a gradual and consistent cooling recorded within the pool until initiation of the 2010 melt season (Figure 5.9 and Table 5.10). The potential for pools such as this to act as winter refugia is highlighted when accumulated degree days are compared. In total A4 amassed 947.35 degree days between day 9th September 2009 (day 252) and 1st August 2010 (day 213) compared to 71.10, 245.32, and 554.90 at K1, K4 and K8 respectively. That was despite maximum temperatures at A4 peaking at 10.28°C, lower than both K4 (10.39°C) the site closest to it and much lower than K8 (13.45°C). It must be remembered that temperatures within the pool were those in the open water and it is likely that regions of higher temperature exist at different places within the pool.

Table 5.12 - Descriptive statistics for near bed temperatures at K1, K4 and K8 within the main channel and in A4, a pool within the lower braided section (postulated fish overwinter refugia) between 9th September 2009 (day 252) and 1st August 2010 (day 213). SD = Standard deviation, DD = degree days.

Site	Mean (°C)	Max (°C)	Min (°C)	SD	DD
K1	-1.46	3.77	-8.03	1.94	71.10
K4	0.57	10.39	-1.52	1.65	245.32
K8	0.63	13.45	-5.33	3.95	554.90
A4	2.90	10.28	0.07	1.62	947.35

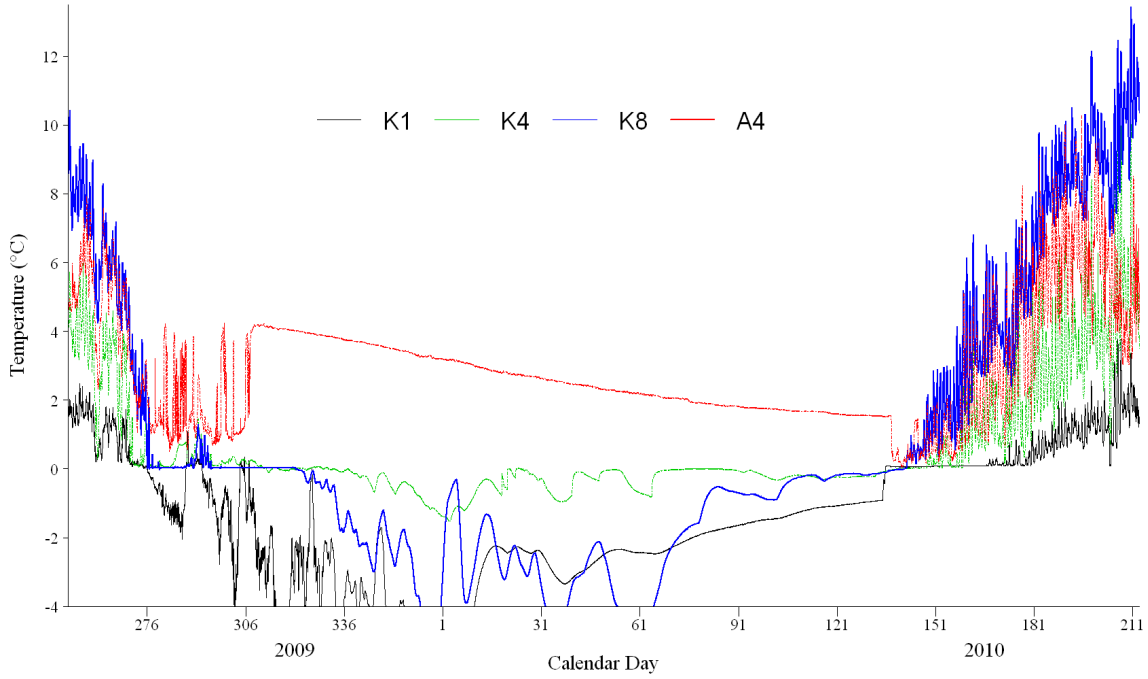

Figure 5.19 – Near bed temperature data from K1, K4, K8 and A4 between 9th September 2009 (day 252) and 1st August 2010 (day 213). Collected to investigate the potential of thermal refugia within the lower braided section (Figures 3.2b and 3.4)

5.5 Discussion

The three aims of this investigation were to characterise water column thermal variation, to identify the extent to which this relates to different hydro-climatological variables and to improve understanding of the processes driving thermal diversity of surface waters in the arctic. This high resolution data set has enabled the characterisation of surface water temperatures within Kårsavagge, has identified key regions of thermal variation and the following section discusses processes driving this variability. It highlights the complex interactions between water source, water storage, geomorphology (both at the whole catchment and local scale), aspect and hydro-climatological conditions that drive water temperature (Clark *et al.*, 1999b, Arscott *et al.*, 2001, Brown *et al.*, 2009)

5.5. i) **Longitudinal thermal variation**

The thermal regimes of main channel sites showed variability both within the main study period but also over winter. Most sites dropped below freezing for the majority of the winter; however, average daily temperatures at K2 only dropped below freezing for 33 days over the 2007-2008 monitoring period and for only 2.5 hrs during the 2008-2009 seasons. This contrasting observation may mark the occurrence of liquid water. At K2 the stream flows through a bedrock gorge section. It is possible that groundwater upwelling occurs along bedding planes or may occur due to channel confinement (Malcolm *et al.*, 2005, Cadbury *et al.*, 2008).

The longitudinal pattern of thermal variation within Kårsavagge fits the pattern observed in other glacierized catchments with average temperatures increasing with distance from source. The average rate of thermal increase from K1 to K9 of 0.52°C Km^{-1} during the entire summer study period is comparable to that observed by Uehlinger *et al*. (2003) and Cadbury *et al*. (2008), but much less than the maximum of 7.0 °C Km^{-1} reported in Brown (2005). Thermal discontinuities in the form of lakes and braided sections interrupt the pattern of downstream increase. This pattern is also inconsistent temporally, ranging from 0.58 °C Km-1 to 0.38°C Km^{-1}. Rates of temperature increase are greatest between K1 and K2 peaking at 1.94 °C Km^{-1}during Period 3. This high rate of increase is due to the relatively low thermal capacity of small channels closer to the source (Caissie, 2006) and is accentuated in this section by braiding which increases the width: depth ratio. Air-water correlation coefficients in these upper sections are generally in the order of 0.8 to 0.9 ($p < 0.001$), further illustrating the influence of atmospheric forcing (Webb and Zhang, 1997, 1999).

Diurnal patterns in discharge are interrupted during Periods 2, 5, 6 and 7 but are clearly present in the upper basin within the other four periods and there is an increase in the strength of the this diurnal signal over the course of the melt season. This pattern is likely to be related to the gradual retreat of snow exposing the lower albedo glacier ice to direct solar radiation (Hannah *et al.*, 2005). Mean discharges in 2008 decreased over time in the order period 1> period 3> period 4; standard deviations increase in the opposite direction (period 4> period 3> period 1). Water temperature peaks at the glacial site occur earlier relative to daily air temperature maxima as the season progresses reflecting the cooling impact of glacially derived flow. The lack of an associated flow increase may simply be due to the reduced temperatures during the period of maximum glacial exposure. The lack of the expected glacial pattern of temperature within the main channel (i.e. a gradual decrease in temperatures from June to September) illustrated by for example Uehlinger *et al.*, (2003) is due to the limited extent of glaciation within the catchment. In the Val Roseg, where Uehlinger *et al.*, (2003) worked 30% of the catchment was glacierized compared to 1.3% of Kårsavagge.

The thermal patterns observed at K3, are characteristic of a snowmelt fed stream, with high average temperature and a very high thermal range compared to main channel sites. Correlation coefficients are high, though generally lower than other sites above the lakes. This is probably due to local morphological and source conditions. The channel is steep and deeply incised, which reduces the potential for solar heating, at least close to the confluence with the main glacial channel. During period 2 the correlation coefficient decreases and this is related to the sharp fall in temperature associated with the second rainfall event, a similar response was displayed on day 205 of the 2009 melt season.

These temperature decreases are not observed in any of the other channels, nor is a similar decrease associated with the first rainfall event in 2008. The cause may be a localised increase in ablation (i.e. the slewing of a large slab of snow/ ice) caused by relatively warm rainfall rather than cooling associated with rainwater impact as suggested in Cadbury *et al.*, (2008) or localised heavy rain, which appeared to be the cause of the dip in 2009.

5.5. ii) **Influence of the Lakes**

Lakes have been described as serial discontinuities (Robinson and Matthaei, 2007) and have been shown to increase and stabilize water temperature (Hieber *et al.*, 2002, Robinson and Matthaei, 2007). Average thermal accumulation rate within the first lake of Kårsavagge (0.82°C km-1) was less than that observed in the proglacial lake in Val Roseg (2.14 to 3.93°C km-1) (Uehlinger *et al.*, 2003), and less than the rate of accumulation in the upper basin (1.47 °C km-1). The short residence time (130 days see Figure 3.6) and specific bathymetry of Lake Bajimus Gorsajavri may negatively impact its potential to act as a heat reservoir (Ward and Stanford, 1983, O'Brien *et al.*, 1997). This may be further hampered by its location in a steep sided valley. Another factor may be that the potential heat source impact is negated by the lakes position in the longitudinal profile. Glacier-fed lakes studied elsewhere, for example, in the Val Roseg are fed directly by a glacier. The impact of these proglacial lakes on water temperature will be large by virtue of the very low temperature. Water entering the first lake has been warmed across two braided sections so will be closer to the regions ambient equilibrium temperature. This being the case one would expect the greatest impact of the lake to be a

reduction in diurnal and potentially seasonal thermal variability simply by virtue of it being a large body of water to heat up/ cool down. Though not a significant heat source through the majority of the study, during period 4, warmest average water temperatures were recorded at K7. This implies that the lakes provide some thermal buffering towards the end of the summer relative to downstream reaches. The issue of the lakes is further complicated by correlation coefficients from Period 8 (K6 = 0.94, K7= 0.88). During Period 8, K7 has low thermal variability compared to K6, which becomes higher. This would follow if the first lakes capacity for thermal inertia is conferred by its volume but the second by its bathymetry, although there is no data to categorically prove this theory. Correlation coefficients between air and water temperature at the lake outflows during periods one, three and four are the lowest recorded due to these being the periods of rapid, i.e. diurnal air temperature change at most sites against which the lakes display a degree of inertia. Differences in longitudinal accumulation of degree days were marked, ranging from 156.8 at K1 to 1178.5 at K9. This is comparable to the 176 to 1227 DD reported by Uehlinger *et al.* (2003) for an alpine basin.

5.5. iii) **Lateral thermal variation**

The potential for lateral variation within a glacial floodplain has been illustrated by several authors (e.g. Mosley, 1983, Uehlinger *et al.*, 2003, Brown *et al.*, 2005) as has the impact of water source on thermal habitat variability (e.g. Ward, 1994, Brown *et al.*, 2005, Robinson and Matthaei, 2007, Hannah and Brown, 2008). Thermal variation was marked over both seasons within the top braided section of Kårsavagge, the average temperature ranged from 2.77°C at B1 to 8.76°C at B10. Though taken over a shorter

period (July to late-August compared to June to mid-September), this range is comparable to the 2.3-10.0°C observed by Uehlinger *et al.* (2003). This is particularly interesting when it is considered that the lateral variation in Kårsavagge occurred over <0.3km^2. The reason for this high degree of thermal variability appears to be a combination of the different dominant water sources and channel morphology. Indeed in Tukey analysis average daily temperature conditions separated by over 7km along the main glacial channel fell into the same groups as those from sites separated by a few meters. Further evidence for this lateral-longitudinal equivalence is provided by the degree day counts; which, for corresponding time periods are similar at sites within the upper braided section and the main channel.

Thermal response of channels in the upper braided section to air temperature variation and weather patterns were broadly consistent with patterns observed within the main channel. Correlation coefficients were high except for dips during period 4 and 5. The reduction in correlation during period 4 is probably associated with an increase of glacially sourced water as mentioned above for K1. This is corroborated by cross correlation coefficients which show the timing of water temperature maxima shifting forward relative to that of local air temperature from period 2 to period 4, in agreement with the hypothesis of increased cooling melt water. The return to approximate concurrence between timings of air and water temperature maxima in Period 5 may reflect the reduced flows associated with cooling temperatures. This increases the impact of atmospheric forcing and/or reduced proportion of glacially sourced flow during the series of rainfall events. Period eight illustrates year to year thermal response as although

it covers roughly the same section of the summer as period 5, glacial sourced flow remains relatively high, retaining discordant water and air temperature maxima.

Inspection of temperature duration curves for sites along the glacial main channel (Figure 5.9) illustrates the correlation between distance from glacier terminus and thermal variability. The gradient of the lines increases from B1 to B7. However B11, an intermediary between sites B1 and B7 in terms of location displays a much steeper curve than may be expected. This is particularly true of higher temperature values, and may represent greater thermal responsiveness to increasing air temperatures. Although on the main glacial channel, B11 is situated just downstream from the input of a mixed groundwater/snowmelt fed tributary, which is too shallow to house a temperature logger. The influence of this tributary input may account for the unexpectedly high thermal variation experienced at B11, see below. Thermal response at B5 is more extreme even than that observed at B11; however the cause of this is less clear and may relate to local geomorphology (i.e. high channel width to depth ratio) or a signal from a non-determined input.

B11 appears to demonstrate a switching of dominant water source over the 2008 melt season. During Periods 2, 3 and 4 B11's pattern of thermal response is intermediate between the glacial main stem and the north facing snowmelt streams. However, by period 5, B11's mean temperature reflects that of sites along the glacial-fed main channel and diurnal pattern is almost indistinguishable from B7. This change would appear to be associated with the reduced late season flows and shift of water source. Just upstream of B11 a groundwater seep and snowmelt channel converge then flow into the main channel. Whilst flowing, they maintained an elevated temperature at B11. The reduction of

snowmelt in late summer leads to contraction of surface channel length (Robinson and Matthaei, 2007) and likely results in a reduced shallow groundwater recharge as in Smith *et al.* (2001). Both of which would lead to an increasing glacial influence at B11. The thermal patterns at B11 are a clear illustration of the temporal shifts in stream source dominance suggested by Brown *et al.* (2003; 2009) in the ARISE classification tool.

The impact of rainfall events on stream water temperature are highly variable with some authors reporting a significant impact (Brown and Hannah, 2007) whilst others report limited impacts (Cadbury *et al.*, 2008). The results from Kårsa suggest that the impact of rainfall input are evident in river flow but have limited direct thermal consequences. The highest discharges over the entire study period were associated with rainfall events at all gauging stations, being most prominent at K2 and B12, where melt water buffering is reduced. However there was not any shift in the very high correlation coefficients with air temperature. This was true for both the main channel and sites across the braided section. The implication of this finding is that water contributing to these elevated flows is already in the system. Rather than Hortonian overland flow dominating water provision to channels, the increased discharges are due to older groundwater being forced into the channelized system by infiltration of rainfall around the basin (Maidment, 1993). The main thermal impact of rainfall appears to be a reduction in insolation through cloud cover (Poole and Berman, 2001). All sites from the main glacial channel and across the braided section record their lowest maximum temperature from Periods 2-5 despite air temperatures higher than those in Periods 4 and 5 (the lowest maxima where associated with the high flows of the initial snowmelt period). There is a sharp reduction in water temperature at K3 associated with the rainfall events on day 207 in 2008 and 205 in 2009,

but as explained above, this is probably due to an ablation event increasing the input of cold melt water rather than rainwater inputs (Cadbury *et al.*, 2008).

5.6 Conclusions

The aims of this chapter were to characterize water column thermal variation, to identify the extent to which this thermal variation is driven by different hydrological, climatological and spatially derived basin variables and to improve understanding of the processes driving the thermal diversity of surface waters within Arctic glacierized basins. River thermal variability identified within Kårsavagge is not as large as that observed in some glacierized Alpine basins; however the scales over which this variability occurs make it very significant. Indeed the capacity for such small scale lateral thermal variation has not been reported previously. The dominant factors controlling this range of water temperatures appear to be atmospheric forcing and water source with significant contributions from channel morphology and season. The annual variation in thermal heterogeneity produced by the interaction of these factors are influenced by depth of annual snowpack, rate of snowline retreat, timing of spring melt, as well as the timing, extent and intensity of precipitation events. Climate change predictions for the Arctic include a shifting of spring melt to earlier in the year and an increase in precipitation (IPCC, 2007). For Kårsavagge this would (in the short term) lead to a longer period dominated solely by glacial melt resulting in reduced stream water temperatures. Any increase in regional summer precipitation would be offset by the local rain shadow cast from the Abisko Mountains. This may be compensated for to some degree by higher rates of winter snowfall (Kohler *et al.*, 2006), though this brings with it other consequences

such as increased discharge and reduced bed stability which also have ecological implications.

Chapter 6 - Water Source Dynamics of Kårsavagge

6.1 Introduction

Recent warming trends have coincided with the recession of many glaciers in the Arctic and globally (Gurnell *et al.*, 2000; Walsh *et al.*, 2005); and the predicted change in climate will lead to a shift in the timing or volume of meltwater inputs into high latitude hydrological systems (Ling and Zhang, 2002; Barnett *et al.*, 2005; Milner *et al.*, 2009). Changes in the timing and extent of meltwater input will affect many catchment hydrological processes and are anticipated to have major implications for ecological communities (Milner *et al.*, 2009; Callaghan *et al.*, 2004c). These communities are adapted to strong seasonality of river flow and other habitat variables (Danks, 2004; Downes, 1965). A shift in seasonality or dominant source of river flow will have negative impacts upon these highly specialized local species assemblages (IPCC, 2001). If the present day range of habitats can be identified and dominant processes governing the functioning of the hydrological regime elucidated, impacts of predicated climate change can be investigated effectively both in relation to shifts in hydrological input, but also how the system is likely to respond. This chapter contributes to the understanding of how Arctic systems may respond to climate change by presenting analysis of water chemistry samples collected from around Kårsavagge over the 2008 and 2009 field seasons. These data are used to identify dominant water sources and from this an analysis of temporal shifts in water source dominance has been made.

6.1. i) **Work on Arctic/ Alpine water sources**

The range and seasonality of sources within a glacierized catchment presents a unique set of challenges to hydrologists wishing to identify the dominant processes governing its hydrochemical regime. Significant contributions to proglacial stream discharge can be made by, some or all of, seasonal snowmelt, glacier melt and rainfall depending on the latitude, altitude, local climate envelope, basin properties (e.g. geology) and extent of basin glacierization (Malard *et al.*, 1999; Brown *et al.*, 2003; Hannah *et al.*, 2005; Hodgkins *et al.*, 2009). The relative proportions of these sources of bulk (total) stream flow and, more importantly, the rate and pathway by which they are transmitted to the main channel determines stream physico-chemical conditions (Brown, 2002; Brown *et al.*, 2006a; Cadbury *et al.*, 2008) and this has implications for aquatic biota (Burgherr *et al.*, 2002; Friberg *et al.*, 2001; Brown *et al.*, 2006d).

Brown *et al.* (2006c) have illustrated the potential of using bulk water solute concentrations to identify key conceptual water sources based on assumptions regarding dominant weathering processes. This work builds on previous models describing the seasonal evolution of proglacial stream water provenance (e.g. Tranter *et al.*, 1993a; Gurnell *et al.*, 2000; Hannah and Gurnell, 2001; Brown, 2002). Most of these models identify at least two, occasionally three distinct water sources. Typically 'quick-flow' describes waters with short transit times subject to low water:rock ratios and subsequently low solute concentration (Tranter *et al.*, 1993a; Brown *et al.*, 2006c). In contrast, waters transmitted through the 'distributed' glacier drainage system has much higher concentrations due to slower transit and high water:rock ratios (Tranter *et al.*, 1993b; Brown *et al.*, 2006c). A third, 'groundwater', or base flow, component can be

identified where it is possible to isolate delayed subglacial flow (Brown *et al.*, 2006c; Malard *et al.*, 1999).

The generally accepted transitions in water source dominance within a glacierized catchment are: (1) start of melt season quick-flow from initial snowmelt ,(2) mid-season glacier distributed system flows followed by (3) end of season base flow from groundwater (Hannah and Gurnell, 2001; Malard *et al.*, 1999). This relates not only to the seasonal depletion/ recharge of the various hydrological reservoirs but also to the development of a subglacial drainage system which opens up allowing more water to access reactive mineral species (Brown, 2002).

6.1. ii) **Dominant weathering processes in glacial environments**

Proglacial streams acquire solutes from two main sources; atmospheric deposition and weathering of mineral deposits (Brown, 2002). Atmospheric deposition includes precipitation and dry deposition. In many catchments this provides the majority of chloride in the form of sea salt (Sharp *et al.*, 1995a) and variable amounts of acidic nitrate and sulphate aerosols depending on regional and seasonal inputs (Hodgkins and Tranter, 1998). The temperature regime of glacierized regions dictates that a large proportion of precipitation falls as snow; and release of solutes from frozen waters delivers a characteristic pulse of atmospherically sourced chemical species to the proglacial system at the start of the melt season (Hodgkins and Tranter, 1998) due to preferential elution of ions from the snowpack (Williams and Melack, 1991; Cragin *et al.*, 1995). Following this initial peak, solute concentrations in snow and ice melt are relatively low (Tranter *et*

al., 1987). When these highly dilute waters come into contact with the abundance of reactive surfaces (i.e. rock flour) that present trace minerals (i.e. pyrites and calcites) for weathering in a glacierized system (Tranter *et al.*, 1993a; Sharp *et al.*, 1995a; Anderson *et al.*, 1997; Brown, 2002) the solute acquisition can be high. Rivers draining glaciated catchments can have annual solute fluxes in excess of comparable rives in temperate or tropical regions despite the seasonal cessation of flow that occurs in winter (Anderson *et al.*, 1997; Hodson *et al.*, 2000).

The dominant cation recorded in most glaciated systems is Ca^{2+}, followed by Mg^{2+}, K^{+} and Na^{+} depending on local lithology. Accordingly, the dominant anion is usually HCO_3^{-}, followed by SO_4^{2-} (Sharp *et al.*, 1995b; Blum *et al.*, 1998; Hodgkins *et al.*, 1998; Fairchild *et al.*, 1999b; Hodson *et al.*, 2000; Darmody *et al.*, 2001; Brown, 2002; Singh and Hasnain, 2002; Brown *et al.*, 2006c). These ions are released by the following weathering reactions (Lafreniere and Sharp, 2005):

1) Carbonation

   a. of carbonates.

$$(Ca, Mg)CO_{3\,(s)} + CO_{2\,(aq)} + H_2O \Leftrightarrow (Ca, Mg)^{2+}{}_{(aq)} + 2HCO_{3\,(aq)}^{-} \qquad \textbf{Equation 6.1}$$

   b. of silicates (calcium and alkali)

$$CaAl_2Si_2O_{8(s)} + 2CO_{2(aq)} + 2H_2O \Leftrightarrow Ca^{2+}{}_{(aq)} + 2HCO_{3\,(aq)}^{-} + H_2Al_2Si_2O_{8(s)} \qquad \textbf{Equation 6.2}$$

$$(Na, K)AlSi_3O_{8(s)} + 9H_2O + 2H_2CO_{3\,(aq)}$$

$$\Leftrightarrow AlSi_2O_5(OH)_{4\,(s)} + (Na, K)^{+}_{(aq)} + 2HCO^{-}_{3\,(aq)} + 4H_4SiO_{4\,(aq)} \qquad \textbf{Equation 6.3}$$

2) Oxidation of Pyrite

$$2FeS_{2(s)} + 4H_2O + 6O_{2\,(aq)} \rightarrow Fe_2O_{3\,(s)} + 4SO_{4(aq)}^{2-} + 8H_{(aq)}^{+}$$ **Equation 6.4**

3) Neutralisation of acid aerosols

$$H_{(aq)}^{+} + NO_{3\,(aq)}^{-} + (Ca, Mg)CO_{3\,(s)} \Leftrightarrow (Ca, Mg)_{(aq)}^{2+} + HCO_{3(aq)}^{-} + NO_{3\,(aq)}^{-}$$ **Equation 6.5**

4) Oxidation of organic carbon (Sharp *et al.*, 1999)

$$C_{org\,(s)} + O_{2(aq)} \Leftrightarrow CO_{2(aq)} + H_2O_{(aq)} \Leftrightarrow H_{(aq)}^{+} + HCO_{3\,(aq)}^{-}$$ **Equation 6.6**

5) Simple dissolution

a. Of gypsum

$$CaSO_{4(s)} \overset{H_2O}{\Longleftrightarrow} Ca_{(aq)}^{2+} + SO_{4\,(aq)}^{2-}$$ **Equation 6.7**

b. Of halite

$$NaCl(s) \overset{H_2O}{\Longleftrightarrow} Na_{(aq)}^{+} + Cl_{(aq)}^{+}$$ **Equation 6.8**

Carbonation requires a proton [H^+] donor, this is most often supplied by dissolution of carbon dioxide, forming carbonic acid (Eq 6.1), occasionally by dissolution of acid aerosols (Eq 6.5) or else the oxidation of sulphides (Eq 6.4) (Brown, 2002).

$$4FeS_{2(s)} + 16CaCO_{3(s)} + 15O_{2(aq)} + 14H_2O \Leftrightarrow 16Ca^{2+}_{(aq)} + 16HCO^{-}_{3\,(aq)} + 8SO^{2-}_{4\,(aq)} + 4Fe(OH)_{3(s)}$$

Equation 6.9

This coupling of sulphide oxidation (SO) and carbonate dissolution (C-D) (Eq 6.9) has been shown to be important in some glacial environments (Sharp *et al.*, 1995b; Hodson *et al.*, 2000). Tranter *et al.* (1993a) suggested that the SO-CD reaction pathway was confined mostly to the subglacial distributed system; however, Fairchild *et al.* (1999b) found that coupled pyrite reactions were prevalent in some regions of the progalcial zone. Assuming limited dissolution of gypsum, ratios of SO_4^{2-} : HCO_3^- (in equivalents) can be used to indicate the relative importance of the SO-CD pathway (Fairchild *et al.*, 1994). A ratio of 1:1 suggests dominance of SO-CD, but lower ratios point to other sources of HCO_3^- being a more important source of bivalent ions (Hodson *et al.*, 2002b).

Rates of silicate weathering are slow compared to those of carbonate or pyrite (Anderson, 2005), as a result, it is only the highest residence time flowpaths, that attain high concentrations (Hodson *et al.*, 2000). Silicates also suffer from non stoichiometric dissolution (i.e. the rate of release of elements does not match the composition within the

mineral), with comminuted material enabling ion exchange from within the silicate matrix (Anderson *et al.*, 1997).

6.1. iii) **Mixing models to elucidate flow pathways**

Brown *et al* (2006c) used the spatial segregation of these weathering processes to elucidate the interaction of groundwaters with quick-flow and distributed (subglacial) flow in a small alpine glacierized catchment in the Pyrenees. This approach relies on the identification of distinct hydrochemical end members for conceptual water sources, which is not always possible in complex environments like proglacial zones (Fairchild *et al.*, 1999b).

6.1. iv) **Isotopes to elucidate meteorological events responsible for different flows**

Stable isotope studies have been used on their own, and in conjunction with major ion chemistry to identify water sources in different environments (Theakstone and Knudsen, 1996 ; Fairchild *et al.*, 1999b; Laudon and Slaymaker, 1997;Carey and Quinton, 2004). The fractionation of heavy and light isotopgules of water during phase change provides a conservative marker of water from particular events such as specific rainstorms or melts (Gat, 2010). During phase change to higher energy states such as melting or evaporation, lighter isotopogules move up preferentially and as a result the residual water is enriched in the heavier isotopes (Araguas-Araguas *et al.*, 2000; Gat, 2010). Solid phase precipitation retains the isotope signature of formation and therefore is more depleted with respect to heavier isotopes than liquid precipitation which equilibrates with the air-

mass through which it falls. This depleted signature, and the relative depletion of oxygen compared to hydrogen can be used to identify flow sourced from melt water or rain waters (Gat, 2010).

6.2 Research gaps and aims

Despite the potential of chemical end-member mixing analysis (EMMA) to elucidate water sources and their contribution to bulk stream flow, there still exists the question of its wider applicability, given the variation within glacierized catchments. Tranter (1996) illustrated that similar drainage pathways may be present under both Arctic and Alpine glaciers. This study builds upon the work of Brown *et al.* (2006c) in the Pyrenees and other studies into proglacial stream hydrology (e.g. Tranter, 1996; Hodson *et al.*, 2000; Hannah and Gurnell, 2001) by investigating the potential of EMMA to elucidate dominant processes controlling stream discharge of Kårsavagge, a small glacierized catchment in the Arctic.

The key aims are:

1) To identify dominant controls on meltwater hydrochemistry.

2) To identify and characterise discrete water sources using hydrochemistry

3) To attempt to quantify the variability in the relative contributions of these different water sources to bulk stream flow in space (down-catchment) and over time (seasonally).

6.3 Methodology

6.3. i) **Site description**

Kårsavagge is a small glacierized catchment in Northern Sweden (See chapter 3 for full description). Schistose rocks dominate the Kårsavagge. Resistant Mica-Schists of the Seve-Köli complex form the bulk of valley sides and floor but two windows in this upper layer, one at the head of the valley and another between the two lakes reveal outcrops of Hard Schists and dolomite of the Abisko nappe (Rapp, 1960; Snowball, 1991; Lindström, 1987). The surface geology of the whole region is predominately exposed bedrock overlain by a thin layer of glacial and glaciofluvial sand containing various caliber rocks (Josefsson, 1990a). Soils are not present on the top plateau of the Kårsavagge Kårsa valley with surfaces made of exposed bedrock and high caliber glacial debris.

6.3. ii) **Sampling protocol**

Snow pack samples were taken at the start of each field season. Weekly water samples at the top three main channel sites K1, K2 and K4 were collected twice daily at low (06:00-09:00 h) and high flow (14:00-16:00 h) to characterize the diurnal variability in hydrochemistry associated with the daily cycles of meltwater generation. The size of the catchment (28km from top to bottom) prohibited a diurnal sampling effort at all sites along the main channel. Weekly samples were taken from the lower three sites K6, K8 and K9. Lateral sampling was done in an exploratory fashion in 2008, but had more structure in 2009, with extensive water samples from the upper braids (samples labelled

B – see Figure 3.1,3.2 and 3.3) taken twice and single opportunistic samples taken from the lower braided delta (samples labelled A [ground water stream and tributaries] and C [main glacial stream and tributaries] – see Figures 3.1, 3.4 and 3.5). Water chemistry collection and analysis are discussed in the methodology chapter (chapter 4).

6.3. iii) **Data analysis**

Analysis of water samples was undertaken following Brown (2004). Due to issues with analytical equipment, cation concentrations for 2008 have been excluded from the analysis. 2008 anion and silica data proved sound and so have been included in EMMA. 2009 water sample data were subjected to analyses using Principal Components Analysis (PCA) with VARIMAX rotation in R (R-Development-Core-Team, 2010; Revelle, 2010). Principal components were used to identify the major controls on water sample chemistry (after Hodson *et al.*, 2002b). Following the Kaiser's Criterion factors with eigenvalues<1 were rejected (Kaiser, 1960).

6.3. iv) **Crustal, Marine and Aerosol sources of ions**

Solute concentrations were separated into crustal, marine and aerosol (snow pack) derived components following Sharp *et al.*, (1995b). All NO_3^- and Cl^- was assumed to have derived from atmospheric deposition and, using this, marine contributions of Ca^{2+}, Mg^{2+}, Na^+ and K^+ were removed by calculating standard sea water ratios to Cl^- (Holland, 1978). Atmospherically derived SO_4^{2-} concentrations associated with acid aerosols were

calculated using average snow Cl^-:SO_4^{2-} ratios following (Sharp *et al.*, 1995b). The prefix '*' is used to denote crustally-derived concentrations.

6.3. v) **Partial pressures of CO2**

Partial pressures of CO_2 ($p[CO_2]$) are useful in determining dominant weathering processes (Fairchild *et al.*, 1994). Higher partial pressures of CO_2 relative to atmospheric concentrations can act to increase chemical weathering rates and low partial pressures of CO_2 imply that reactions are using CO_2 faster than it can diffuse back into solution (Raiswell, 1984). Estimates of log $p(CO_2)$ were derived using the open access computer program WateQ4F, (Ball and Nordstrom, 2004).

6.3. vi) **EMMA -Defining end members:**

Solute concentrations in the quick-flow end member were estimated as the average from melted snow samples. Groundwater solute end member concentrations were estimated from the average from clearly identified groundwater springs. Estimation of solute concentrations in the distributed system from direct measurement was logistically impossible and, hence, was estimated as the concentration at the upper sampling site on the final morning of summer field work when it can be assumed that the majority of flow was sourced from this pathway. Although assuming constant end member hydrochemistry has been highlighted as introducing uncertainties, due to potential seasonal shifts in end member concentrations (Soulsby *et al.*, 2003), this is an accepted limitation of the method. It was deemed that uncertainties introduced by assuming

constant end member concentrations would be less than those generated in trying to estimate weekly variation in end member concentrations from two samples. Indeed, exploratory analysis revealed these constant end members upheld the assumptions of the model, bounding other data points in a Si: SO_4^{2-} cross plot, which constantly shifting end members did not.

6.4 Results

6.4. i) **Summary of site hydrochemistry**

Water chemistry samples displayed variation both spatially and temporally within Kårsavagge. As such, a description of patterns observed longitudinally is followed by a description of samples covering the rest of the basin.

Table 6.1 – Mean solute concentrations of dissolved ions from sites distributed longitudinally along the Kårsa river (K1-K9). TDS = Total dissolved solids;Data from 2009.

	Concentration of dissolved ions (µeq L^{-1}) [StDev]								($mg\ L^{-1}$)		
	Cl^-	SO_4^{2-}	NO_3^-	Na^+	K^+	Mg^{2+}	Ca^{2+}	HCO_3^-	SiO_2	TDS	pH
K1 (n=22)	15.83 [8.57]	197.64 [84.03]	2.88 [0.85]	19.26 [6.81]	16.72 [6.44]	75.50 [26.14]	194.01 [64.37]	87.19 [28.66]	1.18 [0.23]	22.6 [7.02]	7.67
K2 (n=22)	15.90 [7.44]	184.25 [53.97]	2.78 [0.92]	19.34 [5.47]	16.96 [6.35]	75.03 [23.42]	230.52 [65.04]	142.07 [39.77]	1.35 [0.26]	25.85 [7.08]	7.31
K4 (n=22)	16.08 [5.20]	188.13 [57.59]	3.12 [0.95]	21.29 [4.20]	16.76 [4.94]	78.01 [21.52]	237.93 [57.47]	143.88 [37.05]	1.24 [0.24]	26.64 [6.23]	7.34
K6 (n=11)	30.15 [1.72]	174.32 [11.19]	3.84 [1.26]	33.20 [4.41]	20.48 [4.66]	83.69 [6.91]	250.20 [18.66]	176.04 [26.41]	1.38 [0.12]	29.22 [2.24]	7.51
K8 (n=11)	30.24 [5.38]	214.08 [24.52]	2.65 [1.27]	37.56 [6.33]	19.38 [4.48]	100.77 [8.29]	245.48 [13.88]	144.56 [29.99]	0.99 [0.24]	29.21 [1.58]	7.16
K9 (n=11)	30.18 [5.75]	210.18 [24.14]	2.92 [2.09]	34.47 [3.80]	17.96 [1.07]	104.94 [8.73]	274.19 [12.74]	186.41 [15.86]	1.06 [0.16]	31.99 [1.41]	7.75

With the exception of K6, average values of total dissolved solids (TDS) show a steady increase from the site closest to the glacier (K1), to the site furthest downstream (K1) (Table 6.1). The value for K8 is slightly higher than that for K9, the reasons for which are discussed below.

The dominant cations across all water samples are Ca^{2+} and Mg^{2+}. The concentration of Ca^{2+} is much greater than that of Mg^{2+}, reflecting the dominance of calcium in the mineral geology of the catchment. As with TDS, concentrations of all cations increase downstream with more elevated concentrations at K6. In contrast, anion dominance is site specific. K1 displays slight SO_4^{2-} dominance but downstream increases in average HCO_3^-, along with negligible changes in average SO_4^{2-}, make this the dominant anion at all lower sites.

Temporal dynamics in the concentration of individual ion species reflect the shifting influence of different water sources of stream flow. The dominant ions and silicate show a gradual increase in concentration over the melt season with ions lacking significant crustal sources (e.g. Cl^-, Na^+ and NO_3) displaying the opposite trend at most sites.

Concentrations of all ion species except Cl^- correlate negatively with discharge; this is concordant with the major source of Cl^- being snowmelt and sources for the other ions being weathering reactions of local rock minerals.

6.4. ii) **PCA analysis**

Axes were retained only if they had eigenvalues greater than one (Kaiser, 1960). For the top two sites (K1 and K2) only PC1 and PC2 met this criterion. K6 retained four PC's and at other sites three PC's were retained. PCA (Table 6.2) separates sites upstream of the first lake, (K1, K2, and K4) from those below by the proportion of variation attributed to the first PC. At the upper sites, PC1 contains over half the total variation (51.9%), with

strong loading upon Mg^{2+}, Ca^{2+}, SO_4^{2-}, K^+, SiO_2 and HCO_3^- as well as NO_3^- at K2. PC2 at all three upper sites is dominated by Cl^- and Na+, nitrate being incorporated at K1 and driving the variation on PC3 at K4.

Analysis of water samples below the first lake relies on half the number of samples so all interpretations are tentative; however there does appear to be a shift in the pattern of the dissolved ion regime. PC1 and PC2 at K6, K8 and K9 comprise ~65% of the total variance and illustrate a separation of ionic species. PC1 from K6 is heavily loaded on Mg^{2+}, HCO_3^- and Ca^{2+} whereas PC2 is strongly loaded on SO_4^{2-} and Cl^- with K^+, SiO_2 and HCO_3^- loading in the opposite direction (Table 6. 2).

Table 6.2 – Principle components loadings on for axis with eiganvalues above 1 for sites distributed longitudinally along Kårsa river (K1-K9). Data from 2009.

	K1		K2		K4			K6				K8			K8		
	PC1	PC2	PC1	PC2	PC1	PC2	PC3	PC1	PC2	PC3	PC4	PC1	PC2	PC3	PC1	PC2	PC3
Cl^-	0.03	**0.95**	-0.09	**0.98**	0.00	**0.90**	-0.27	0.34	**0.65**	0.53	0.18	**0.69**	-0.04	0.63	**-0.78**	0.44	0.09
SO_4^{2-}	**0.94**	-0.01	**0.94**	-0.11	**0.94**	-0.16	0.17	0.14	**0.95**	-0.16	-0.12	**0.73**	0.15	-0.65	**0.95**	0.10	-0.05
NO_3^-	0.13	0.75	0.79	0.44	0.32	0.06	**0.85**	-0.31	-0.13	-0.18	**0.90**	0.45	**-0.75**	-0.07	-0.18	**-0.78**	0.26
Na^+	0.48	**0.83**	0.34	**0.93**	0.63	**0.66**	0.04	0.57	-0.16	**0.65**	0.37	**0.64**	0.44	0.48	**-0.75**	0.57	0.05
K^+	**0.94**	-0.05	**0.91**	0.02	**0.87**	-0.07	-0.16	0.40	**-0.63**	0.59	-0.25	**0.71**	0.64	-0.04	0.13	0.65	-0.51
Mg^{2+}	**0.99**	0.00	**0.98**	-0.04	**0.95**	-0.20	-0.08	**0.92**	0.08	**-0.30**	-0.07	0.44	0.60	**-0.63**	**0.88**	0.33	0.28
Ca^{2+}	**0.97**	-0.11	**0.98**	-0.08	**0.97**	-0.13	-0.11	0.83	**0.40**	-0.34	0.14	-0.50	**0.84**	-0.06	0.60	0.43	**0.64**
HCO_3^-	0.62	-0.34	**0.85**	-0.06	**0.78**	-0.13	-0.47	**0.90**	**-0.37**	-0.14	0.07	-0.62	**0.68**	0.32	-0.35	0.51	**0.66**
SiO_2	**0.93**	-0.15	**0.80**	-0.42	**0.70**	0.27	0.33	0.21	-0.58	**-0.62**	0.03	**0.51**	0.21	0.46	0.20	0.38	**-0.63**
Eigenvalues	5.19	2.30	5.74	2.21	5.08	1.43	1.20	3.13	2.39	1.71	1.09	3.21	2.76	1.76	3.41	2.26	1.67

The loading pattern on PC2 can be attributed in part to a separation between flow routing patterns. Channelized flow, sourced at the head of the basin will be transmitted to K6 without acquiring ionic species and will retain its relatively high SO_4^{2-} and Cl^- signal. Water routed through soil or groundwater loses this SO_4^{2-} signal to some extent because of increased concentration of dissolved species such as K^+, SiO_2 and HCO_3^-. PC1 at K8 is strongly loaded on SO_4^{2-}, K^+, Cl^- and Na^+ and may represent a seasonal reduction in meltwater input. For K8 PC2 is heavily negatively loaded on NO_3^- and positively loaded for Ca^{2+} and HCO_3^-. This can be explained by discharge correlations with those ions dominant in base flow displaying negative correlation and NO_3^- displaying positive correlation. PC1 identified at K9 is related to the seasonal decrease in Cl^- and Na^+ and increasing SO_4^{2-}. PC2 for K9 is heavily negatively loaded on NO_3^- and positively for K^+. The pattern of flows at the lower sites is a gradual decrease from the high discharges associated with the spring melt. Identifying patterns beyond concentration shifts associated with this flow recession becomes increasingly difficult given the ion load at the lower sites (K6, K8, K9) reflects the interaction of a many different smaller catchments, which may be responding to different driving mechanisms.

6.4. iii) **Catchment-wide patterns**

The catchment wide water chemistry samples display more variability than those along the main channel (Table 6.3). PCA analysis identifies key patterns which map onto the different water sources identified during fieldwork. PC1 one is heavily loaded on all of the dissolved species except SO_4^{2-} and separates out samples with relatively a high dissolved load (e.g. B13 groundwater), from those of much lower concentration (e.g. B2 snowmelt). PC1 splits the samples into groundwater's samples along the main glacial channel and snowmelt streams. PC2 is heavily loaded on SO_4^{2-} and the identified groundwater plot out along a continuum on this component. The separation can be attributed to different SO_4^{2-} concentrations at each site and by extension, sub-glacial influence. B16 is situated in the middle of the upstream end of the braided section and it is hypothesized that it derives the majority of its flow from water moving through the headward slope (rather than the valley sides), sourced in the main from sub-glacial melt. B13 is situated on the north side at the downstream end of the upper braids and derives the majority of its flow from valley side hillslope ground waters fed by snowmelt and rainwater percolating through soils/ debris cover.

Flow in other hypothesized groundwater channels is a mixture of the sub-glacial fed groundwaters and snowmelt fed hillslope groundwaters, and as such have a SO_4^{2-} signals intermediate between B13 and B16. The pattern of water samples taken from along the main glacial channel within the upper braids illustrates this further as the input from different side channels shifts the position of the main channel sample within the PCA plot (see Figure 6. 1)

Table 6.3 - Mean solute concentrations of dissolved ions from sites distributed within the upper braided section (see Figure 3.2) of Kårsavagge.

	Concentration of dissolved ions (µeq L^{-1}) [StDev]								(mg L^{-1})		
	Cl^-	SO_4^{2-}	NO_3^-	Na^+	K^+	Mg^{2+}	Ca^{2+}	HCO_3^-	SiO_2	TDS	pH
B1 (n=3)	11.20 [4.10]	149.04 [26.36]	2.19 [0.78]	13.43 [4.30]	11.92 [1.75]	58.84 [10.26]	177.77 [35.93]	98.74 [32.06]	0.64 [0.08]	19.34 [3.46]	7.18
B2 (n=3)	9.21 [4.76]	55.10 [4.98]	3.06 [1.41]	10.08 [4.26]	6.45 [0.58]	25.25 [2.58]	83.29 [7.32]	58.01 [6.28]	0.36 [0.25]	9.50 [0.91]	7.67
B3 (n=3)	9.52 [3.63]	148.49 [21.69]	2.91 [2.15]	13.79 [5.94]	12.64 [1.90]	62.12 [2.98]	185.34 [18.02]	111.55 [45.09]	0.80 [0.09]	20.47 [2.32]	[-]
B5 (n=3)	15.47 [0.41]	121.17 [10.66]	2.09 [1.34]	22.53 [7.50]	12.77 [2.45]	60.30 [7.34]	216.90 [67.51]	173.77 [94.53]	1.08 [0.56]	24.21 [7.59]	7.57
B6 (n=3)	8.37 [2.23]	134.33 [21.20]	2.50 [0.40]	12.06 [3.64]	10.27 [0.28]	50.95 [8.30]	149.43 [10.18]	76.96 [4.22]	0.55 [0.03]	16.39 [0.85]	[-]
B7 (n=3)	12.20 [5.23]	122.40 [23.51]	2.18 [0.63]	20.00 [11.90]	12.03 [0.79]	58.00 [7.17]	197.35 [49.35]	149.50 [78.99]	0.89 [0.36]	21.98 [5.88]	7.63
B8 (n=1)	13.31 [-]	148.74 [-]	1.30 [-]	26.73 [-]	16.40 [-]	67.34 [-]	272.56 [-]	218.39 [-]	1.51 [-]	29.98 [-]	[-]
B9 (n=3)	19.47 [0.05]	118.56 [2.72]	1.42 [0.39]	44.74 [3.14]	19.02 [1.42]	96.51 [8.71]	378.17 [32.91]	397.85 [41.39]	3.43 [0.22]	44.60 [3.79]	[-]
B10 (n=3)	20.44 [1.06]	133.40 [6.88]	1.16 [0.36]	42.43 [5.96]	16.26 [2.49]	88.95 [12.89]	354.12 [64.21]	346.15 [77.06]	2.88 [0.23]	40.91 [6.86]	7.55
B11 (n=1)	9.17 [-]	164.34 [-]	2.09 [-]	15.90 [-]	14.74 [-]	70.22 [-]	215.64 [-]	139.69 [-]	0.99 [-]	23.90 [-]	[-]
B12 (n=3)	16.22 [4.45]	120.43 [18.66]	1.28 [0.61]	24.91 [0.43]	12.12 [1.42]	62.19 [8.09]	190.87 [28.45]	151.39 [20.68]	1.11 [0.20]	22.35 [2.96]	7.08
B13 (n=3)	27.59 [8.01]	60.91 [9.58]	1.36 [0.59]	37.77 [1.30]	8.43 [1.72]	106.86 [14.23]	619.96 [139.64]	683.16 [133.69]	4.16 [0.45]	64.70 [11.77]	7.37
B14 (n=3)	18.97 [4.07]	176.64 [10.04]	1.66 [0.38]	28.95 [0.62]	29.91 [3.36]	100.27 [10.28]	309.79 [23.44]	271.13 [0.10]	1.61 [0.05]	36.52 [2.30]	7.44
B15 (n=3)	14.54 [3.64]	125.30 [21.46]	2.29 [0.61]	28.08 [5.44]	15.08 [3.62]	62.62 [6.44]	194.48 [22.98]	157.65 [11.92]	1.12 [0.18]	23.23 [2.22]	7.41
B16 (n=3)	20.45 [4.10]	219.08 [1.34]	2.47 [0.09]	30.48 [2.04]	39.73 [8.28]	124.03 [4.43]	430.38 [29.02]	382.64 [49.11]	1.91 [0.32]	48.84 [4.07]	7.51

Samples taken from the lower braided section, the channels directly upstream of the first lake (marked either A or C see Figures 3.2, 3.3 & 3.4) are included within the PCA plot to give a broader view on solute concentrations within the upper catchment. The same

pattern is observed with component one separating on the basis of concentration of dissolved species other than SO_4^{2-} and component two heavily loaded on SO_4^{2-} (Figure 6.1). Samples from within the upper braids are less spread out on this plot as longer residence time and therefore more concentrated samples are included. The high SO_4^{2-} concentrations of some of these samples, notably C8 from the lower braided section (see Figure 3.5), may also be supplemented by localized pyrite oxidation as illustrated by their reduced pH.

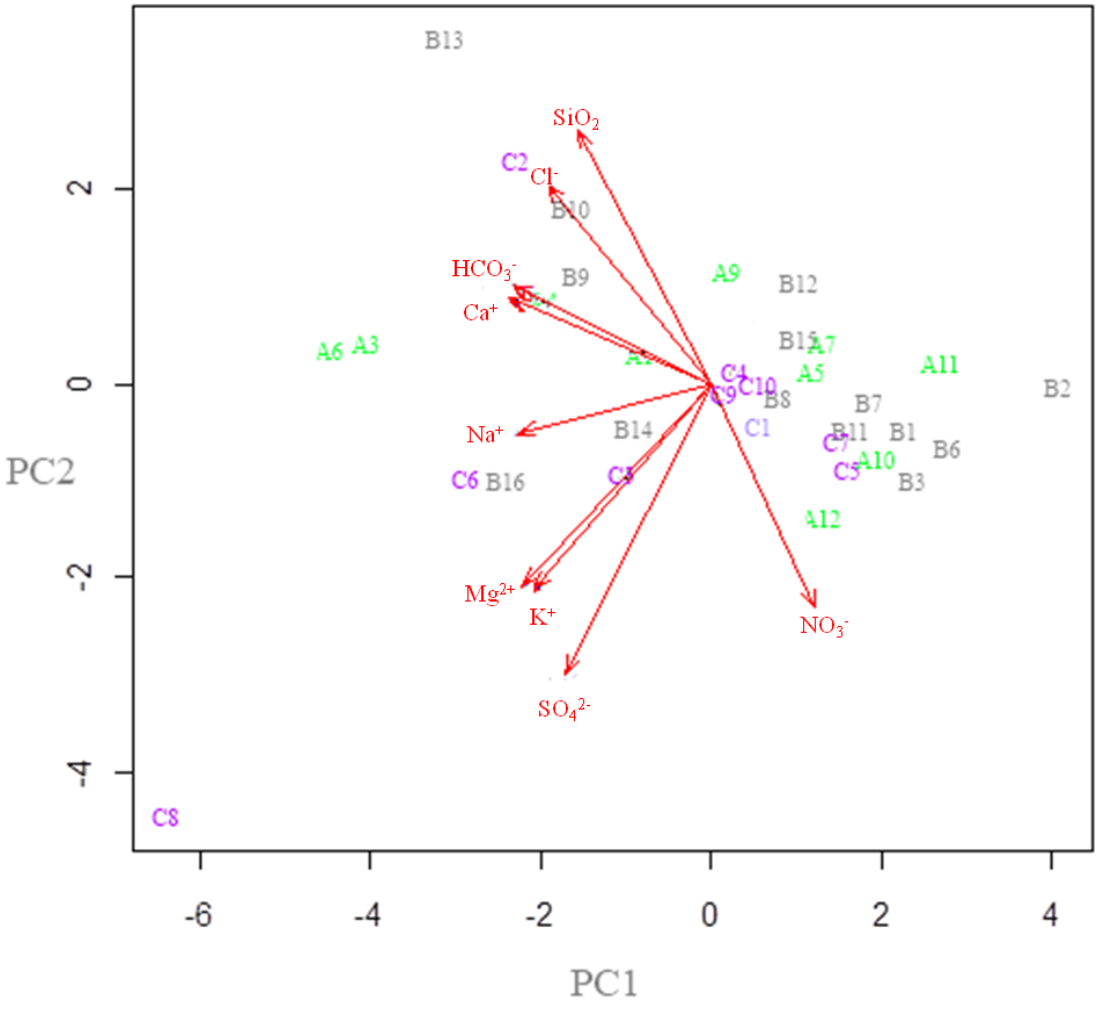

Figure 6.1 – Plot of 1st and 2nd principle component scores for sites across the upper (B1-B16) and lower (A1-A12, C1-C10) braided regions of Kårsavagge. For distribution of sites see Figures 3.1 - 3.4.

Concentrations of the majority of dissolved ions and Si are much reduced in snow and precipitation samples relative to stream concentrations (Table 6.4). Dominant ions in snow samples are HCO_3^-, Cl^- and Na^+. The differences in ion concentration between early and mid-season snow pit samples illustrate preferential elution of certain ion species. Average concentrations of SO_4^{2-} and Mg^{2+} were elevated in SN1 with respect to the average snow concentrations, and within this snow pit the lower third (>0.6m) was more concentrated in terms of these ions than the upper profile. Ca^{2+} concentrations in the early season snow pit are also elevated. In contrast, Cl^-, Na^+ and K^+ concentration are elevated in the mid-season snow pit.

Table 6.4 – Mean solute concentrations of dissolved ions in precipitation samples from Kårsavagge collected in 2009. Total dissolved solids = TDS, Standard deviation = StDev.

	Concentration of dissolved ions (µeq L^{-1}) [StDev]								(mg L^{-1})	
	Cl^-	SO_4^{2-}	NO_3^-	Na^+	K^+	Mg^{2+}	Ca^{2+}	HCO_3^-	SiO_2	TDS
Snow (n=6)	17.76 [9.33]	6.91 [9.69]	1.76 [-]	22.57 [10.48]	6.97 [3.64]	4.85 [4.26]	41.20 [28.09]	49.17 [26.62]	0.00 [0.00]	5.71 [1.65]
Ice (n=1)	2.68 [-]	2.50 [-]	1.69 [-]	19.53 [-]	0.38 [-]	2.73 [-]	18.56 [-]	34.32 [-]	0.00 [-]	3.28 [-]
Rain (n=1)	31.18 [-]	8.62 [-]	3.91 [-]	45.49 [-]	26.02 [-]	5.55 [-]	38.48 [-]	71.84 [-]	0.00 [-]	8.92 [-]

6.4. iv) **Inferred weathering processes**

The dominance of certain ions species and the ratios at which they are found can be used to infer the dominant weathering processes occurring within Kårsavagge. The dominant anions across all stream samples were $*SO_4^{2-}$,* HCO_3^-, $*Ca^{2+}$ and $*Mg^{2+}$, suggesting that the dominant weathering reactions taking place are concerned with the dissolution of calcites. The low C-ratios ($*HCO_3^-$ / ($*SO_4^{2-}$ +* HCO_3^-)) in the main channel are indicative of SO-CD reactions (discussed below further).

In the upper braided section, the C-ratio ranges from 0.40 at sites along the central glacial stream to close to 0.94 at sites fed from hillslope groundwaters with values at other sites sitting along this continuum. This range of values illustrates that different weathering processes are dominant along different flow paths associated with different rock types. Hillslope groundwaters are dominated by hydrolysis of carbonates giving rise to a C-ratio close to unity (Fairchild *et al.*, 1994) with other sites reflecting the extent to which glacial melt-waters mix with this high carbonate input. Indeed the C-ratio of the main channel increases down the upper braided section, probably as a result of this groundwater input.

C-ratios from samples in the lower braids display a similar pattern to that of the upper braids ranging from 0.4 to 0.8. The majority of sites along the main glacial channel illustrate SO-CD dominance with sites on smaller groundwater channels having a more mixed solute provenance.

Molar ratios of $*Na^+ + *K^+ / *Ca^{2+} + *Mg^{2+}$ at all main channel sites were low (0.09 to 0.26) but not insignificant and highlight that, although carbonate weathering is the dominant process,

silicate weathering remains an important process determining ionic load. Average silicate concentrations along these main sites show variations beyond the expected downstream increase. There is an increase from K1 to K2 but concentrations dip at K4 before increasing again at K6. Downstream of K6 average values drop, with K8 and K9 having concentrations lower than K1. The noted elevated ratios of *K/Si observed in other glacierized catchments (diagnostic of higher than average cation: silicate mediated by elevated physical weathering resulting non stoichiometric weathering (Hodson *et al.*, 2000)) are present along the entire length of the river with ratios between 0.7 and 1.5. In contrast to the expected downstream reduction in *K/Si ratio with increased temperature and vegetation, i.e. distance from glacier (Anderson *et al.*, 1997), the average ratios at site K8 and K9 are elevated relative to those in the upper catchment. This may relate to the rapid transmission of glaciated waters to the lower sites and/or the addition of melt waters from other sources or the removal of what little silica is present by the increased diatom populations.

It is clear that the majority of samples along the main sites fall within an envelope describing low silica conditions. It is also apparent that the hillslope groundwaters are exceptions to this, having acquired higher concentrations due to longer residence and therefore higher mineral: water contact time (Brown, 2002). This variability in silicate concentration suggests Si concentrations can be used to identify water input from groundwater sources.

6.4. v) ***p*CO$_2$**

Partial pressures of CO_2 give information regarding the type and rate of weathering occurring. Higher partial pressures of CO_2 relative to atmospheric concentrations act to increase

chemical weathering rates and low partial pressures of CO_2 imply that reactions are using CO_2 faster than it can diffuse back into solution (Raiswell, 1984). Water samples from K1 are depleted in CO_2 relative to atmospheric concentrations (Figure 6.2), indicating that CO_2 is consumed faster than it can be replenished. Although in contact with reactive sediments none of the samples reach saturation with respect weathered minerals. Open system weathering occurs downstream with average $p(CO_2)$ levels reflecting atmospheric $p(CO_2)$ with supply exceeding consumption by weathering and the water being in equilibrium with the atmospheric concentrations.

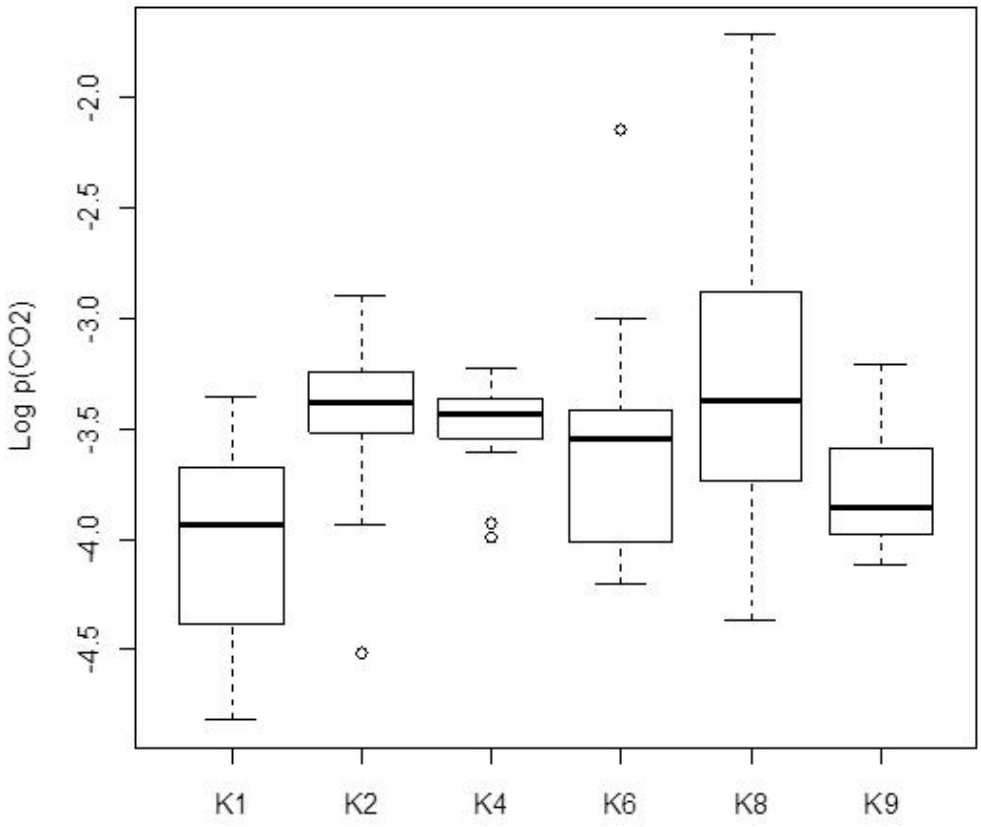

Figure 6.2 - log *p*(CO2) values from main channel sites longitudinally distributed within Kårsavagge: K1, K2 and K4 (n = 22); K6, K8 and K9 (n=11)

6.4. vi) **Isotope Data**

Stable isotope analysis was undertaken to investigate the relative contribution of winter compared to summer precipitation. Stable isotope values for snow and ice show highly depleted values for $\delta^{18}O$ and $\delta^{2}H$. All samples taken in the solid phase sit along a line to the left of the Global Meteoric Water Line (GMWL) with a regression equation of $\delta^{2}H = 7.9\ \delta^{18}O + 18.0$ ($R^2 = 0.97$), illustrating high values of *d*-excess (Figure 6.3). This departure from the GMWL conforms to the model put forward by Jouzel and Merilivat (1984) of transport fractionation on top of the ice/vapour fractionation factor. Liquid meteoric water samples appear to show a very slight deviation from the GMWL gradient, with the line of best fit suggesting that evaporation may act to enrich rain as it falls. Although samples from three events are limited number from which to draw unequivocal conclusions, the evolution of $\delta^{2}H$ scores from one rainfall event on day 182 appear to support this hypothesis as they become more depleted as the event progresses.

Stream water samples across the catchment reflect the dominance of winter precipitation on summer discharge as they plot around the local meteoric water line (LMWL) for snow and ice rather than rainfall. Many of the samples are depleted with respect to ice and snow reflecting fractionation processes within the melting snowpack (Cragin *et al.*, 1995).

This evolution of isotope values of the snowpack can be observed in the stream samples which become more enriched in the heaver isotopes as the melt season progresses. Samples on day 177 and day 189 from snowpacks on the glacier snout and south facing slopes show fractionation within the snowpack with upper layers more enriched due to preferential percolation of lighter isotopogules. This distinction is not observed on north facing slopes

until sampling on day 196 by which time the south facing slopes have a generally more enriched δ2H signature and the reversed pattern with the most depleted layer at the top– possibly due to the reduced fractionation at higher temperatures experienced on these slopes.

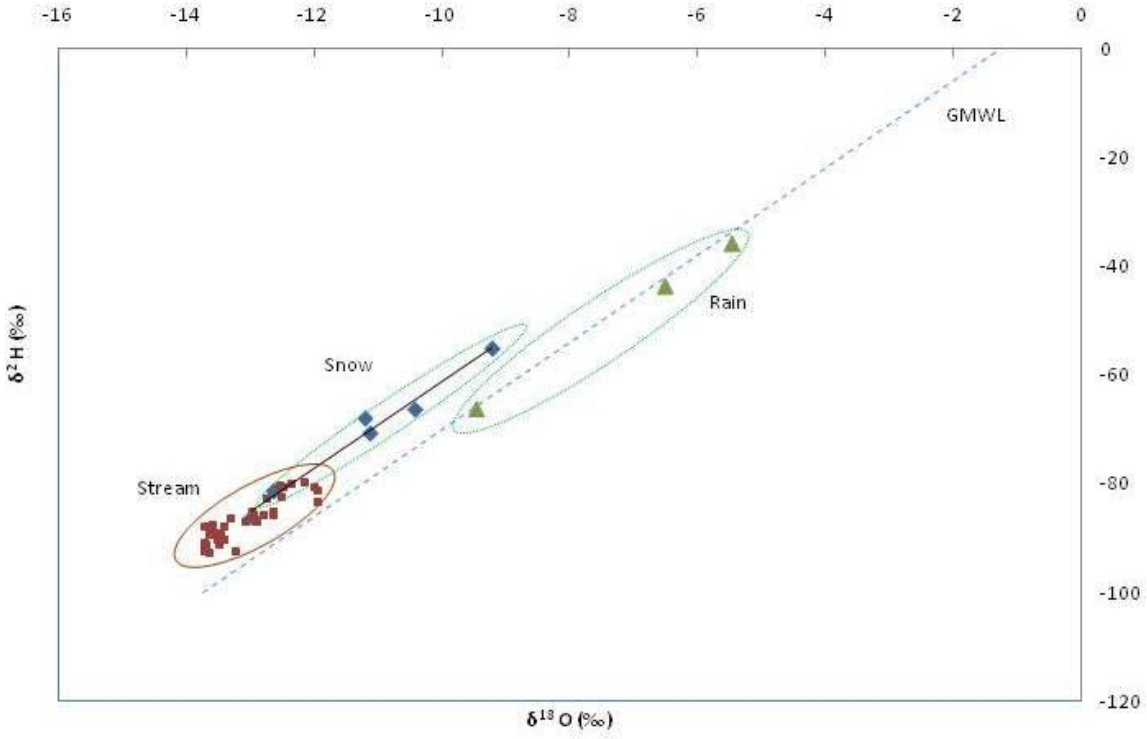

Figure 6.3 – Delta plot of stable isotope data from around Kårsavagge. Rain samples ▲ (n=3), Snow samples ◆ (n=5), stream water samples ■ (n=37). Global mean water line = GMWL.

More detailed information on temporal dynamics is available for K2, K4 and sub-sample of the streams in the upper braided section. Together these illustrate the interaction between the variable δ^2H signature of snowpack sourced water, the more consistent δ^2H glacial melt and the role played by rainfall. The daily pattern of δ^2H (for days without rainfall input) is a gradual enrichment as air temperature rises leading to increased input from relatively enriched

glacial melt, pulling the δ^2H signature of stream water up. As air temperature falls, glacial input reduces and δ^2H returns to the more depleted signature. Rainfall adds an extra dimension to this pattern. In the Kårsavagge it appears rainfall can act in three ways: (1) a heavy downpour may elevate the stream δ^2H by the direct addition of isotopically enriched water, (2) rain may mobilize and flush out pre-event glacial meltwater, increasing the δ^2H of stream water, (3) rain may infiltrate soils and displace the relatively depleted ground/ soil waters depleting the δ^2H of stream water. These three impacts occur over different time scales and events, with impact (1) occurring instantaneously, impact (2) having a delayed response mediated by infiltration rates and impact (3) having a response time in between (1) and (2). Within the upper braided section groundwater shows much reduced daily variability in δ^2H relative to the snowmelt and main glacial streams, although the gradual trend of seasonal enrichment is retained.

6.4. vii) **End Member Mixing Analysis**

A bi-plot of SO_4^{2-} against Si for the 2009 data arranged all bulk melt water samples and the majority of wider catchment samples within a triangular envelope bounded by the three conceptualized end members. End members were defined as Quick-flow, Distributed flow and groundwater following Brown *et al.* (2006c) (Figure 6.4 and Table 6.5). Although cation data from 2008 is suspect, the anion and Si appears to be consistent with that from 2009 so it has also been investigated using the end member mixing model. The Quick-flow component is defined by low concentrations of SO_4^{2-} and Si and comprised snowmelt and fast routed supra-glacial melt. Distributed flow comprises delayed flow through the sub-glacial system with high SO_4^{2-} and intermediate Si concentration estimated from solute concentrations at the top

site. The groundwater component describes longer residence time waters with intermediate SO_4^{2-} and high Si defined using solute concentrations from measured hillslope groundwaters.

Table 6.5 - Concentrations of SO_4^{2-} and Si used in the final End Member analyses.

Water source	Year	End member concentrations	
		SO_4^{2-} (μeqL^{-1})	Si (ppm)
Distributed	2008	300.9	1.90
	2009	417.44	1.67
Quick-flow	2008	14.07	0.00
	2009	6.28	0.00
Groundwater	2008	96.64	4.07
	2009	101.43	4.01

Solute concentrations at the top site reflected the pattern observed in many glacierized basins with SO_4^{2-} and Si showing strong negative correlations with discharge (e.g. Tranter and Raiswell, 1991; Brown, 2002). This correlation can be used to estimate the concentration of SO_4^{2-} and Si in the distributed system as illustrated in Tranter *et al* (1993b) which gave concentrations of: 356.7 μeq L^{-1} SO_4^{2-} and 1.7 ppm Si in 2009; and 300.9 μeq L^{-1} SO_4^{2-} and 1.9 ppm Si in 2008. However, due to logistical constraints, gauging stations had to be removed before the final week of water sampling. As a result, intercept values estimating SO_4^{2-} concentrations for both the 2008 and 2009 were less than final observed values. These final observed values reflected concentrations as the glacial system was closing up, had limited snow and ice-melt and it was therefore felt they would provide more appropriate approximations of distributed flow end-members than those estimated via discharge relationships. However the final observed values of 546.81 μeq L^{-1} SO_4^{2-} and 2.76 ppm Si in 2008 were so removed from the pattern of concentrations prior to the final week of sampling

as to reflect a shift in flowpath rather than a cessation of quick flow input. For this reason, the final concentrations used for the distributed flow path were 417.44 μeq L^{-1} SO_4^{2-} and 1.67 ppm Si in 2009 (estimated from final week samples) and 300.9 μeq L^{-1} SO_4^{2-} and 1.90 ppm Si in 2008 (estimated from discharge relationships).

Concentrations of SO_4^{2-} in the quick-flow pathway end member were estimated from snow and direct glacial samples and remained low over both years with average concentrations of 6.28 μeq L^{-1} and 14.07 μeq L^{-1} in 2009 and 2008, respectively. Si concentrations found in Kårsavagge are relatively high compared to those in some alpine glaciated catchments (Hodson *et al.*, 2002a; Brown, 2004; Krawczyk and Bartoszewski, 2008); however, they do fall within the concentration range found by Thorn *et al.*(2001) in the Karkevagge (a valley located 5km to the North). Concentrations of SO_4^{2-} and Si for the groundwater, high residence time end member was estimated from direct samples of hill slope ground waters. SO_4^{2-} concentrations in these ranged from 50.21 μeq L^{-1} to 150.00 μeq L^{-1} in 2009 giving a mean end member value of 101.43 μeq L^{-1}. Si concentrations in the same samples were high ranging from 3.56 ppm to 4.47 ppm giving a mean value of 4.01 ppm. The 2008 SO_4^{2-} concentrations ranged between 216.32 μeq L^{-1} and 44.74 μeq L^{-1} giving an end member value of 96.6 μeq L^{-1} with silica ranging from 5.1 ppm to 3.3 ppm producing an end member value of 4.07 ppm. End member mixing analysis plots for both 2009 and 2008 are show in Figure 6.4 & Table 6.5.

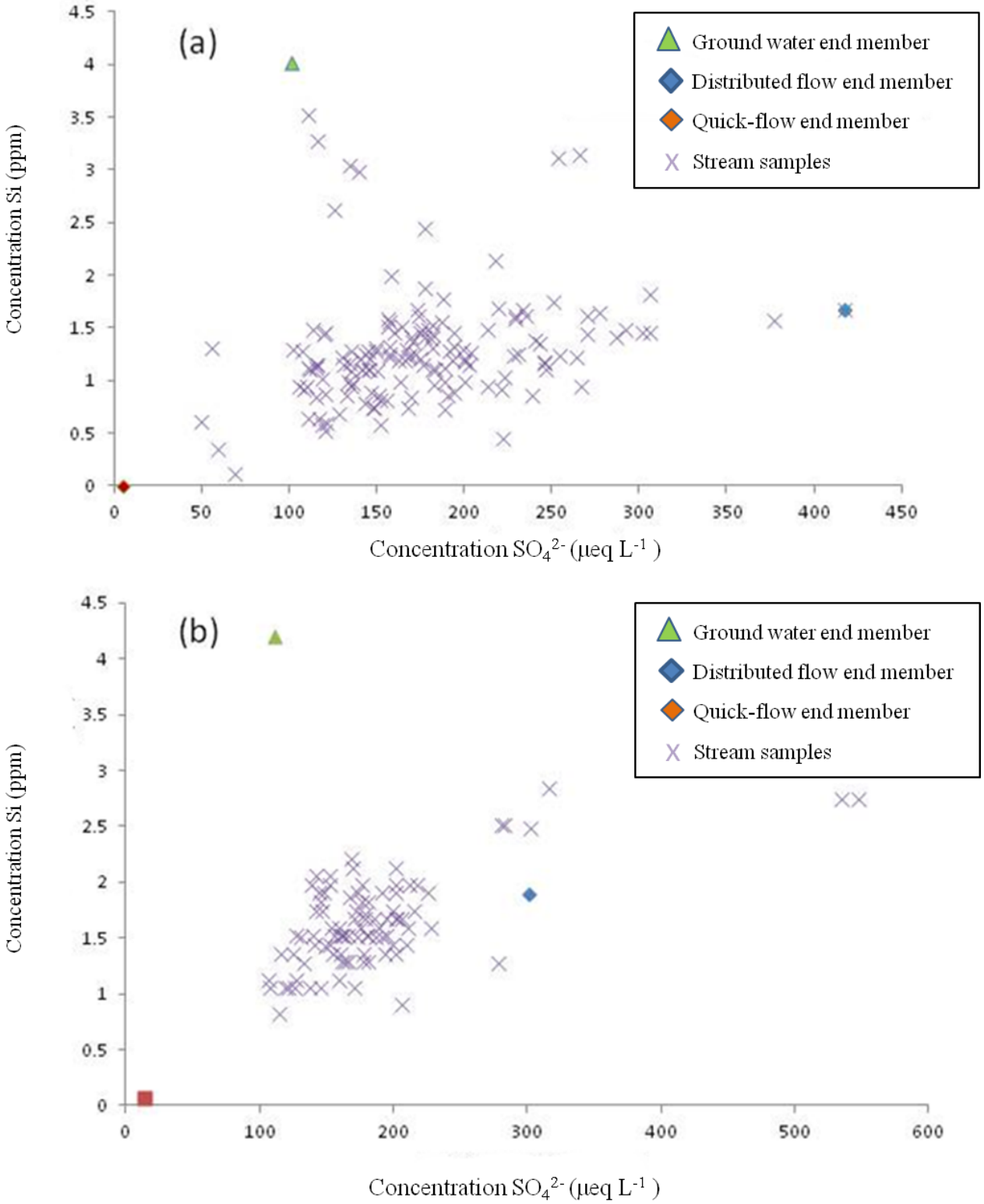

Figure 6.1 – Si : SO_4^{2-} biplots of stream water chemistry samples bounded by end members identified in Table 6.5. (a) Data taken from all 2009 data, longitudinal sites (K1-K9) including sites around upper (B1-B15) and lower (A1-A12, C1-C10) braided sections (longitudinal and lateral sites not differentiated on plot); some extreme sites fall outside end members for the main sites – see text for explanation. (b) Data taken from 2008 longitudinal sites (K1-K9).

6.4. viii) **Inter annual patterns**

The pattern in water source contributions varies between sites but is relatively consistent between years (Figures 6.5-6.10). The sites can be separated into groups based on their position in the catchment, namely: K1, K2 and K4; K8 and K9; K6. K1, K2 and K4 are dominated by quick-flow and distributed flow water sources with average proportions from the groundwater flow path much reduced (10%, 17%, 18% in 2008 and 11%, 17%, 14% in 2009 for K1, K2 and K4 respectively). Groundwater contributions remain relatively constant over each season with average proportions increasing downstream. In 2008 the distributed water source contributed the greatest average proportion to flow (54%) at K1 but in 2009 the proportion from quick-flow and the distributed water source was equal (0.44%). The slight dominance by distributed water source in 2008 was retained at K2 and K4; but, in 2009, this slight dominance shifted in favour of quick-flow.

Inter annual variation was more pronounced at K8 and K9. The distributed water source dominated in both years; however, it accounted for a much higher proportion of flow in 2008 (61% at K8 and 53% at K9) than in 2009 (49% at K8 and 48% at K9) when quick-flow sources almost equalled it (45% at K8 and K9).

In both years K6 was characterized by a relatively consistent contribution from all three sources. Groundwater sources made the greatest contribution to flow at any site along the main channel for both years at K6, but the contribution was higher in 2008 (29%) than 2009 (19%). Quick-flow and distributed flow water sources were the dominant sources in both years at K6 but their relative contribution showed annual variation (Figure 6.8). Quick-flow (35%) and distributed flow (36%) contributions were almost equal in 2008

but in 2009 quick-flow (45%) was the dominant source with distributed flow only contributing 36% of flow.

6.4. ix) **Longitudinal patterns**

Similar seasonal patterns in water source were displayed at K1, K2 and K4 over both years (Figures 6.5- 6. 7). The initial difference in source dominance can be explained by the seasonal melt having progressed further at K2 and K4 at the time of first sample than at K1 which is more elevated and closer to the glacial source. In 2009, after the first sample on day 176, relative proportions at K1 remain fairly constant until around day 223 when the proportion attributed to quick-flow begins to reduce and the proportion from the distributed water source increase. The reduction in quick-flow input began earlier in 2008 than 2009 with proportions falling from day 214 and resulting in greater end of season dominance by distributed flow.

The reduction in quick-flow proportion occurred a week earlier at K2 and K3 in both years; however, in 2008, this was associated with an increase in groundwater contribution which was not observed in 2009. Indeed, in 2008, groundwater contributions rose above those of quick-flow during the final week of sampling for both K2 and K4. In 2009 groundwater contributions only rose above that from quick-flow on the morning of day 250 at K2. Aside from these seasonal trends, the morning and afternoon sampling regime highlighted the daily shift in proportions associated with different water sources which becomes more pronounced as the melt season progressed. As expected there is a general trend of higher quick-flow proportions in the afternoon samples.

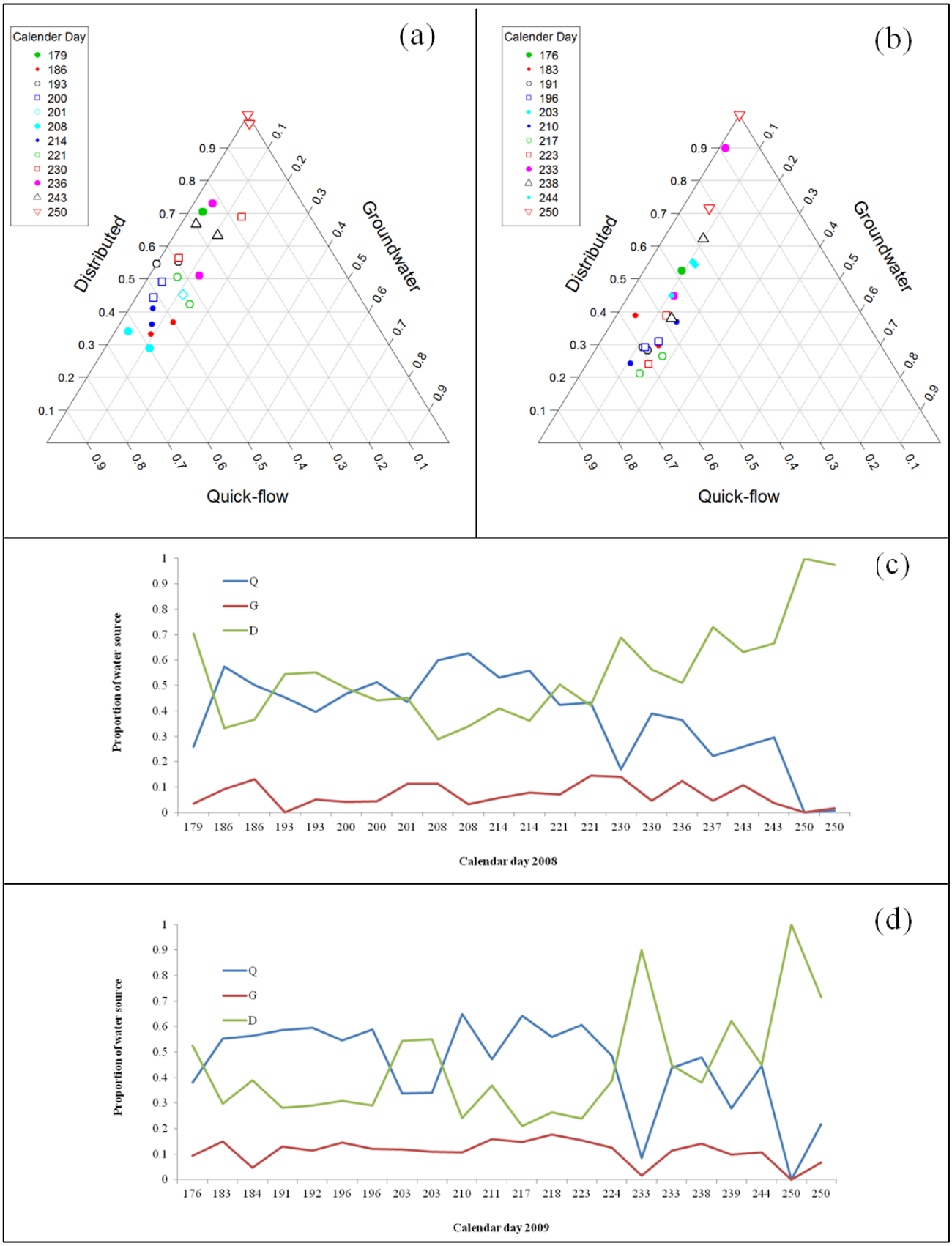

Figure 6.5 – Water source proportions at K1. Proportion of water from Groundwater (G), Quick-flow (Q) and Distributed (D) sources based on the ARISE End-Member mixing model. (a) Ternary plot of water samples from K1 taken on different dates during the 2008 field season; (b) Ternary plot of water samples from K1 taken on different dates during the 2009 field season; (c) Plot of water samples from K1 in 2008 showing the proportion sourced from each postulated end member; (d) Plot of water samples from K1 in 2009 showing the proportion sourced from each postulated end member. Both ternary and line plots are included as the contrasting techniques highlight different aspects of the data – Ternary plots illustrate the seasonal trajectory of a site; Line plots illustrate the temporal shift in each source contribution.

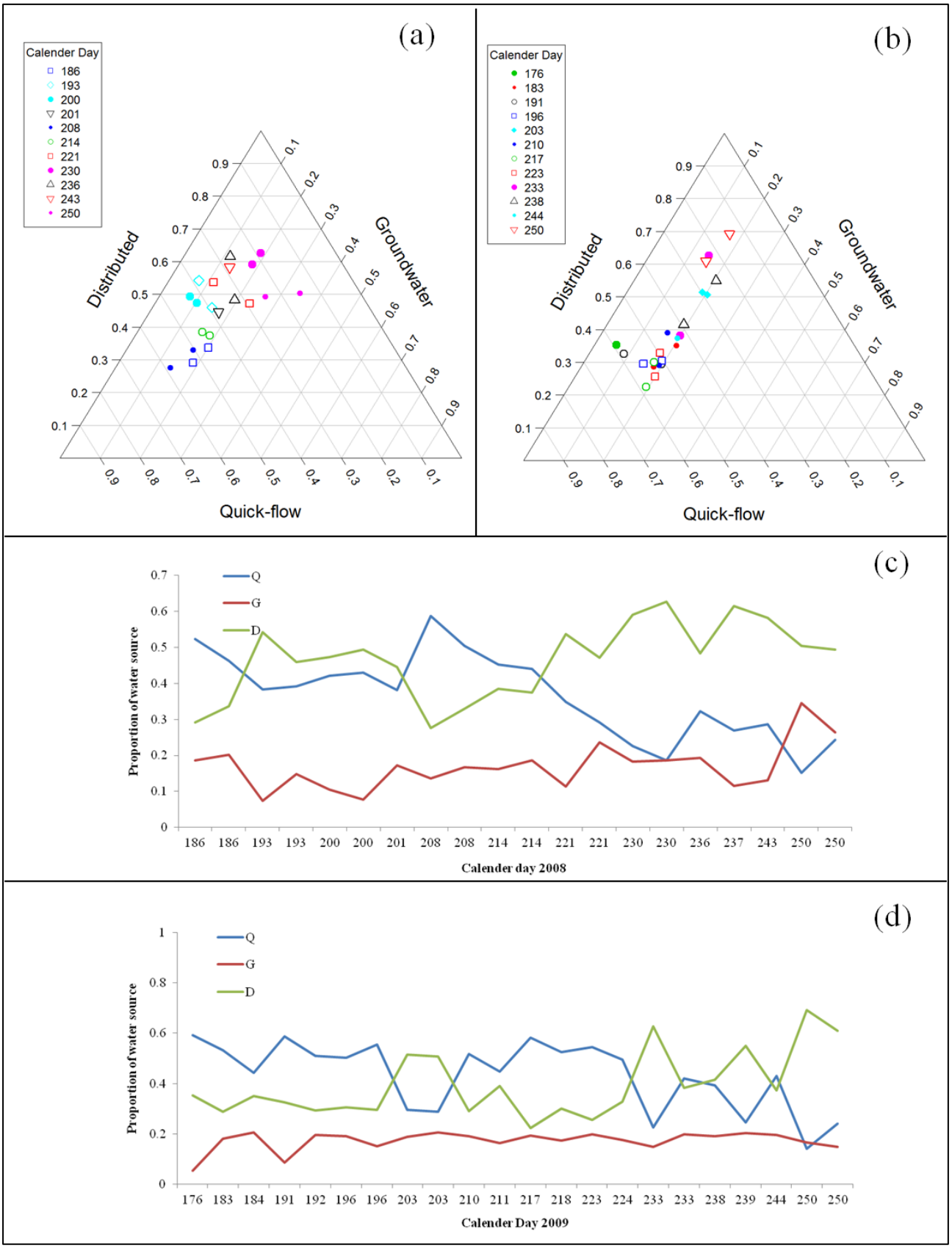

Figure 6.6 – Water source proportions at K2. Proportion of water from Groundwater (G), Quick-flow (Q) and Distributed (D) sources based on the ARISE End-Member mixing model. (a) Ternary plot of water samples from K2 taken on different dates during the 2008 field season; (b) Ternary plot of water samples from K2 taken on different dates during the 2009 field season; (c) Plot of water samples from K2 in 2008 showing the proportion sourced from each postulated end member; (d) Plot of water samples from K2 in 2009 showing the proportion sourced from each postulated end member. Both ternary and line plots are included as the contrasting techniques highlight different aspects of the data – Ternary plots illustrate the seasonal trajectory of a site; Line plots illustrate the temporal shift in each source contribution.

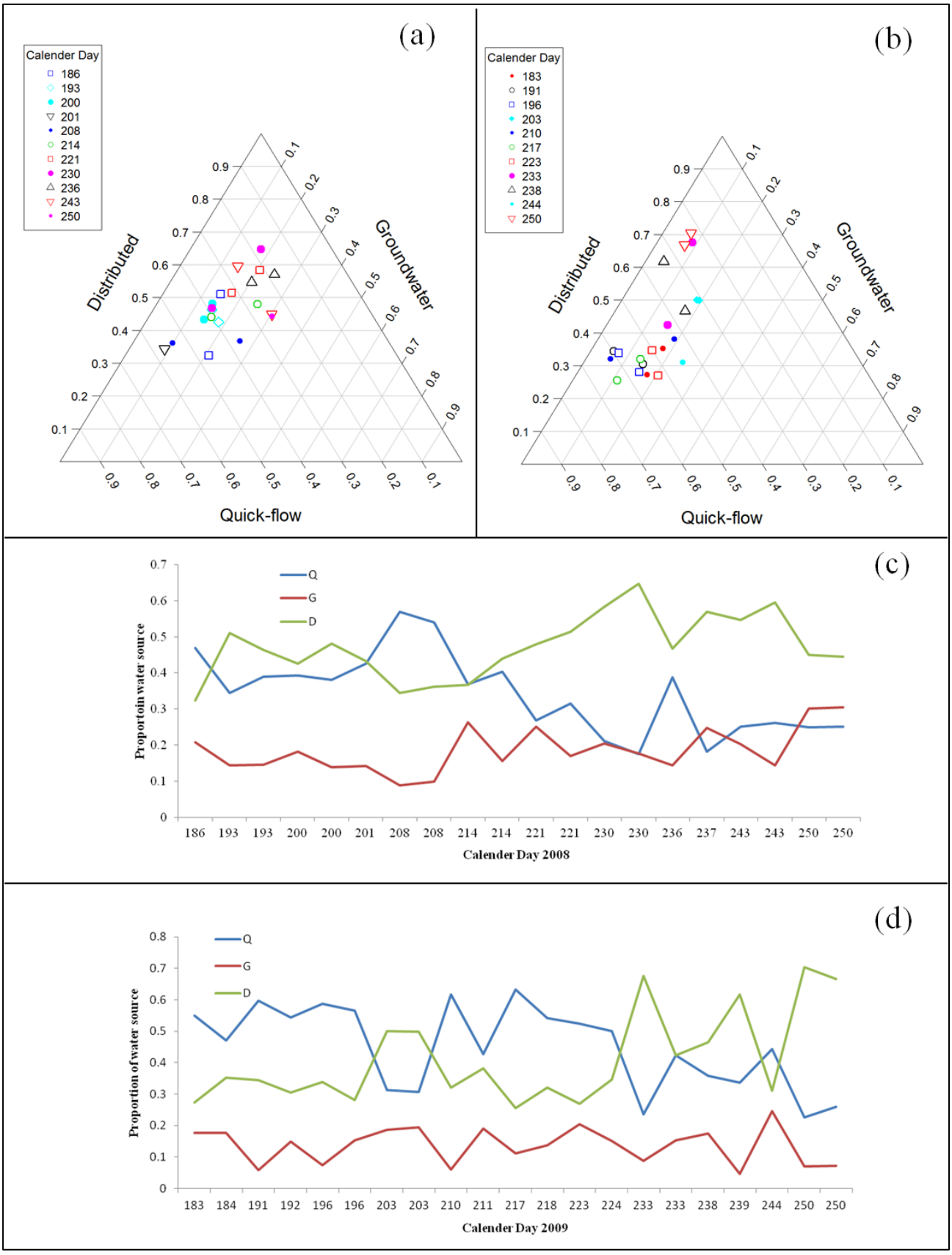

Figure 6.7 – Water source proportions at K4. Proportion of water from Groundwater (G), Quick-flow (Q) and Distributed (D) sources based on the ARISE End-Member mixing model. (a) Ternary plot of water samples from K4 taken on different dates during the 2008 field season; (b) Ternary plot of water samples from K4 taken on different dates during the 2009 field season; (c) Plot of water samples from K4 in 2008 showing the proportion sourced from each postulated end member; (d) Plot of water samples from K4 in 2009 showing the proportion sourced from each postulated end member. Both ternary and line plots are included as the contrasting techniques highlight different aspects of the data – Ternary plots illustrate the seasonal trajectory of a site; Line plots illustrate the temporal shift in each source contribution.

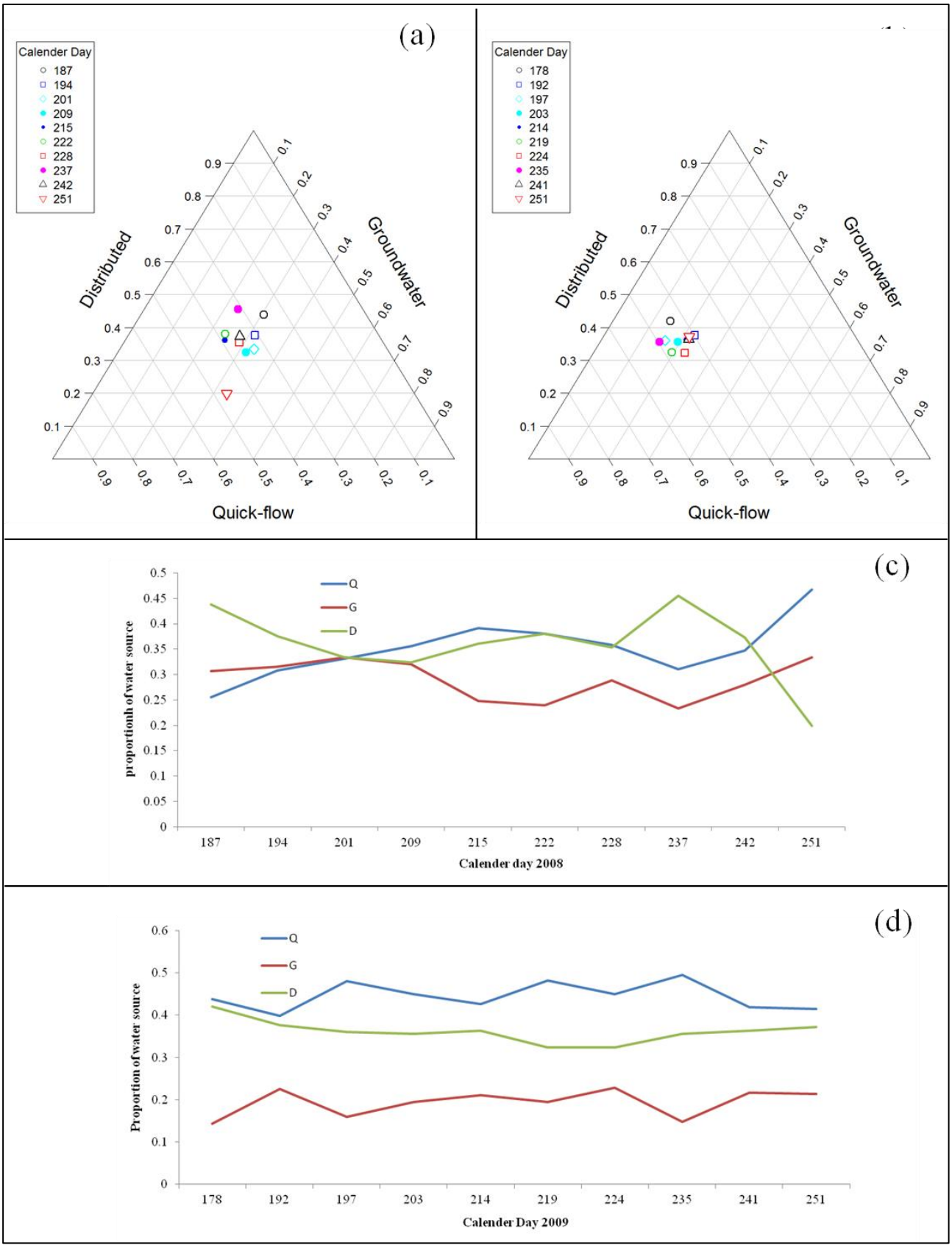

Figure 6.8 – Water source proportions at K6. Proportion of water from Groundwater (G), Quick-flow (Q) and Distributed (D) sources based on the ARISE End-Member mixing model. (a) Ternary plot of water samples from K6 taken on different dates during the 2008 field season; (b) Ternary plot of water samples from K6 taken on different dates during the 2009 field season; (c) Plot of water samples from K6 in 2008 showing the proportion sourced from each postulated end member; (d) Plot of water samples from K6 in 2009 showing the proportion sourced from each postulated end member. Both ternary and line plots are included as the contrasting techniques highlight different aspects of the data – Ternary plots illustrate the seasonal trajectory of a site; Line plots illustrate the temporal shift in each source contribution.

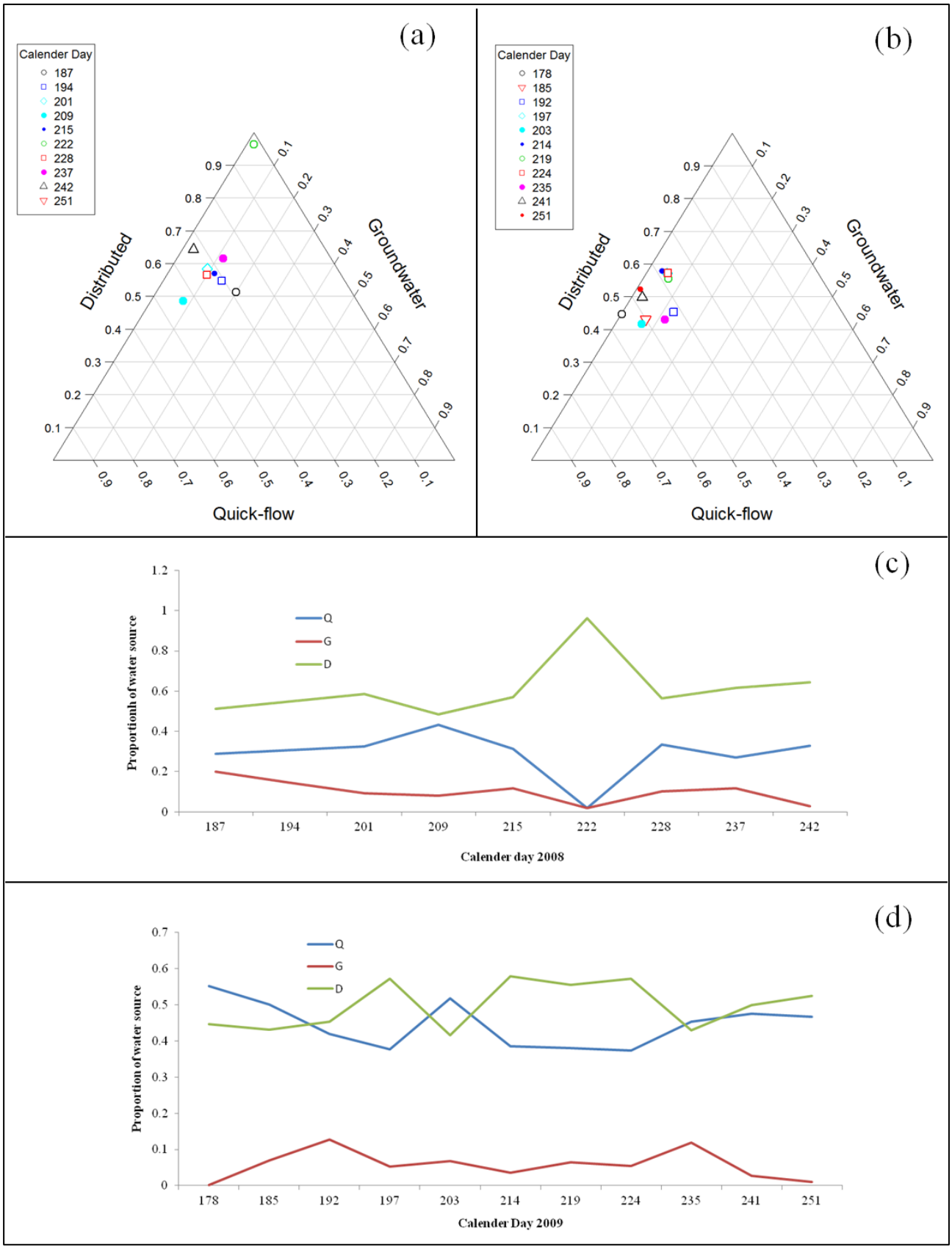

Figure 6.9 – Water source proportions at K8. Proportion of water from Groundwater (G), Quick-flow (Q) and Distributed (D) sources based on the ARISE End-Member mixing model. (a) Ternary plot of water samples from K8 taken on different dates during the 2008 field season; (b) Ternary plot of water samples from K8 taken on different dates during the 2009 field season; (c) Plot of water samples from K8 in 2008 showing the proportion sourced from each postulated end member; (d) Plot of water samples from K8 in 2009 showing the proportion sourced from each postulated end member. Both ternary and line plots are included as the contrasting techniques highlight different aspects of the data – Ternary plots illustrate the seasonal trajectory of a site; Line plots illustrate the temporal shift in each source contribution.

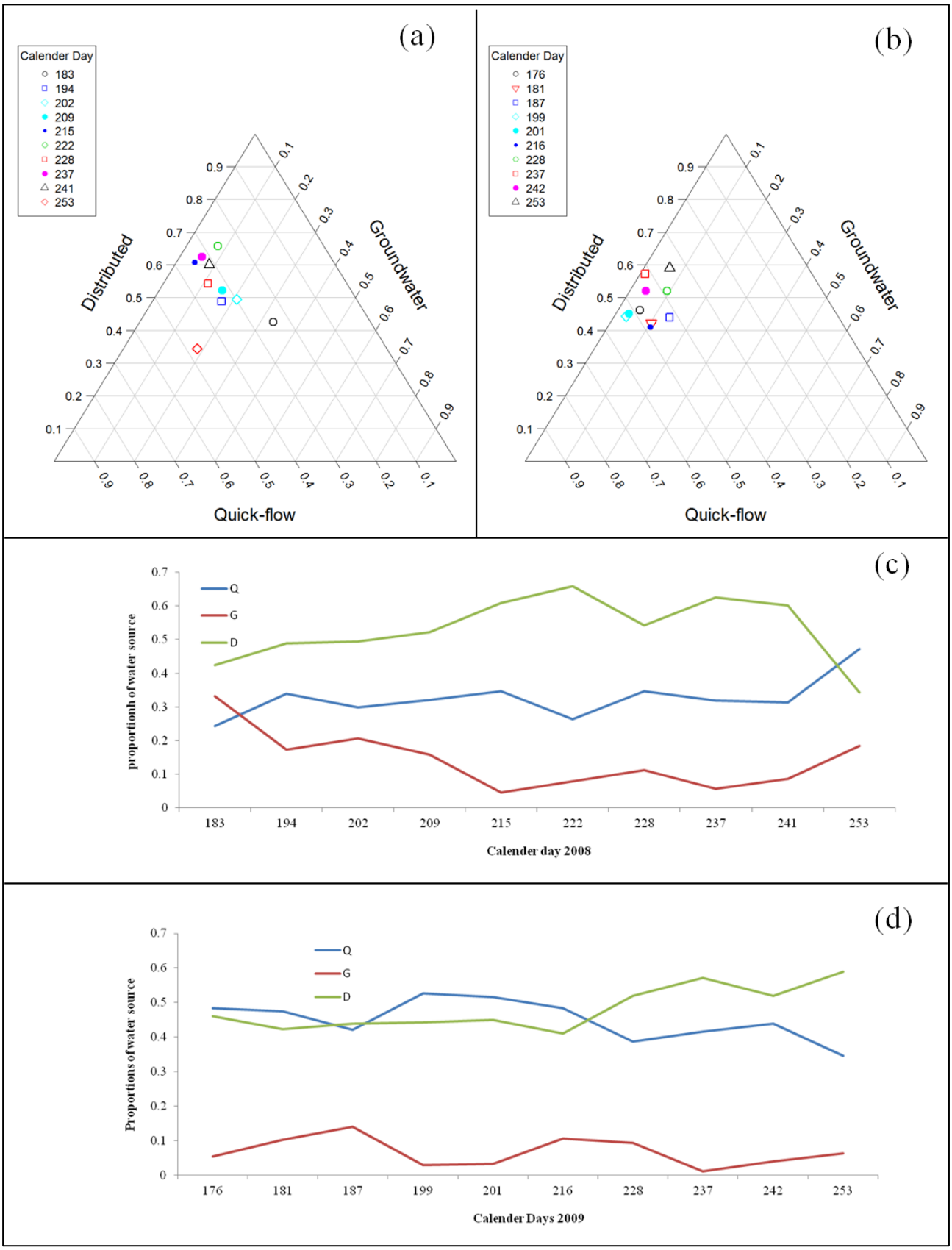

Figure 6.10 – Water source proportions at K9. Proportion of water from Groundwater (G), Quick-flow (Q) and Distributed (D) sources based on the ARISE End-Member mixing model. (a) Ternary plot of water samples from K9 taken on different dates during the 2008 field season; (b) Ternary plot of water samples from K9 taken on different dates during the 2009 field season; (c) Plot of water samples from K9 in 2008 showing the proportion sourced from each postulated end member; (d) Plot of water samples from K9 in 2009 showing the proportion sourced from each postulated end member. Both ternary and line plots are included as the contrasting techniques highlight different aspects of the data – Ternary plots illustrate the seasonal trajectory of a site; Line plots illustrate the temporal shift in each source contribution.

6.4. x) **Lateral patterns**

The identification of conceptual end members for the main channel enabled characterization of the conceptual hydrology experienced by different tributaries, by assuming that they were fed by the same conceptual water sources as the main river. Figure 6.11 plots sites within the upper braided section according the contribution of water from quick-flow, distributed flow and groundwater in 2009.

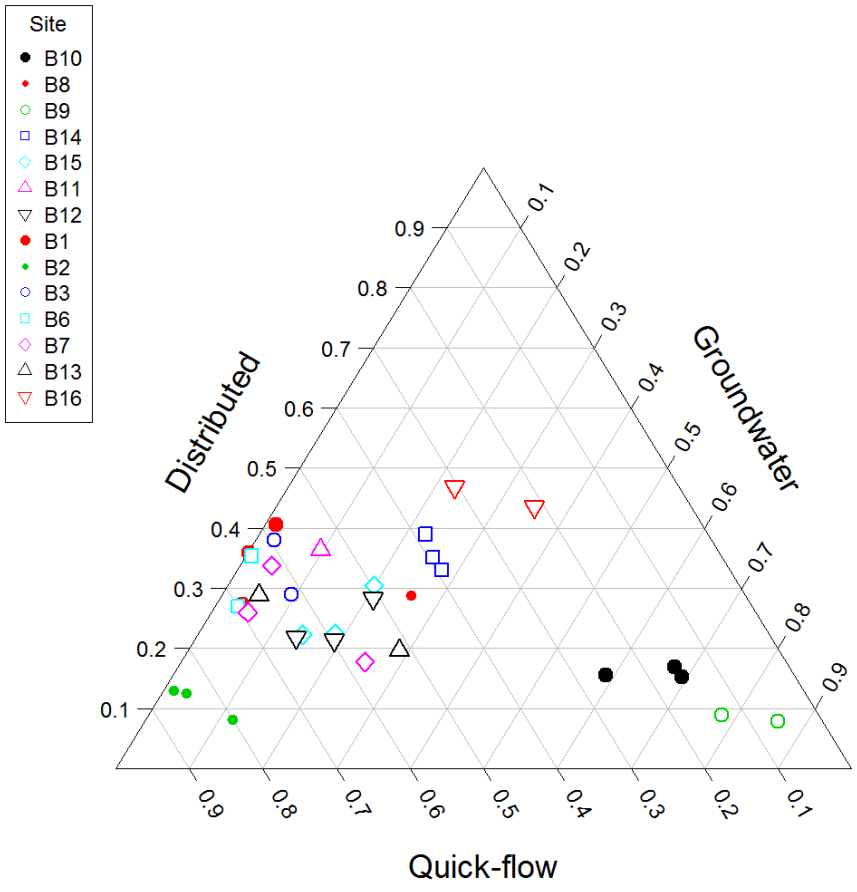

Figure 6.11 – Ternary plot illustrating the proportion of different water sources contributing to samples taken from within the upper braided section (B1-B16) in 2009. Each point corresponds to a different sampling occasion. For distribution see Figures 3.1, 3.2 and 3.4

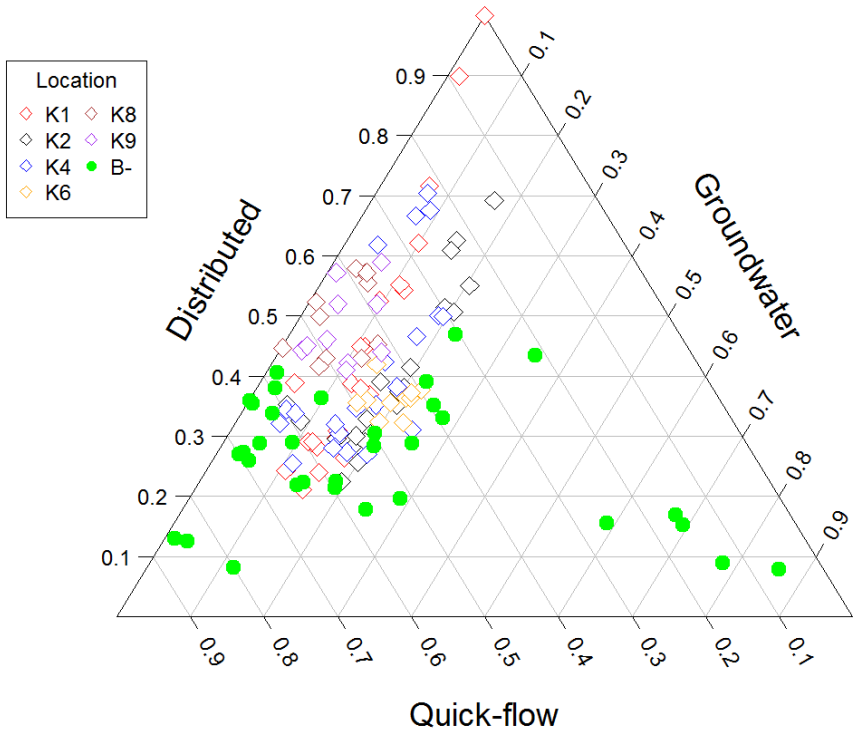

Figure 6.12 – Ternary plot comparing the the proportion of different water sources contributing to samples taken from within the upper braided section (B- = all samples taken from around B1-B16) to sites along the main river channel (K1-K9) in 2009. Each point corresponds to a different sampling occasion. For distribution see Figures 3.1, 3.2a and 3.4.

Water samples taken from within the upper braided sites (B1-B16) are distributed more widely around a ternary plot than samples taken from sites along the main river channel (See Figure 6.12). It may be assumed that this greater range of water source combinations has produced a wider range environmental condition than are found longitudinally. For example B10 and B9 plot out close to the postulated groundwater end member (see Figure 6.11). B2 (a snowmelt stream fed by melt from the southern slope) reflects chemistry dominated by the quick flow water source and as one would expect those sites on the main glacial channel (B1, B3, B11 and B7) plot out in the same region as samples from the main monitoring sites (K1-K9). It is interesting to note that on each sampling occasion there is a shift in position within the ternary from B1 at the start of the braids to

B7 at the end of the braids reflecting the addition from the different tributaries which results in a slight drift in plot space towards the groundwater end member (see Figure 6.11).

6.5 Discussion

The aims of this chapter were to identify the dominant controls on stream water hydrochemistry, to characterize discrete water sources and quantify their respective contribution to stream flow at different sites within the basin. The following pages use the detailed sampling within Kårsavagge to address these aims, first by identifying the dominant weathering processes operating within the catchment and then discussing how these help to separate out different water sources. Finally the spatial and temporal contribution from each of these sources is considered.

6.5. i) **Solute processes**

Solute concentrations in the snowpack were low as the sampling only caught the tail end of initial spring melt, missing the associated initial pulse of eluted ions (Hodgkins and Tranter, 1998). Preferential elution of ions occurs in the order SO_4^{2-}, NO_3^-, Cl^- (Brimblecome *et al.*, 1986) and SO_4^{2-} concentrations in the bottom layer of the earliest snowmelt sample were higher than both samples closer to the surface of the snowpack or later in the season. This is due to the eluted SO_4^{2-} migrating through the snowpack with the initial melt waters and this sulphate pulse may be responsible for the relatively high initial concentration of SO_4^{2-} at the top site. The absence of this pulse at the other sites

can be accounted for by the earlier onset of melt and hence loss of SO_4^{2-} from the snowpack in the lower catchment.

6.5. ii) **Water source identification**

The stable isotope data confirms that melt waters form the dominant source of flow at all sites throughout the entire melt season with limited input from local rainfall. This dependency though not unexpected given the catchments situation in the rain shadow of the Abisko Mountains highlights the potential impact of climate change which is predicted change the volume and timing of snowmelt.

Quick-flow snowmelt and later in the season glacial melt lowered concentrations in the bulk melt waters as is illustrated by the diurnal fluctuations in concentration at the top three sites (2.5 km from the glacier), with total dissolved solids (TDS) from morning samples generally much higher than those taken in the afternoon. Although logistical constraints prevented morning and afternoon sampling at sites below the lakes, thermal data suggest that diurnal fluctuation at these sites is much damped (See chapter 5 for further details). Excluding the early season pulse of eluted ions, hydrochemistry for the majority of the melt season is dominated by solutes sourced from crustal weathering within the proglacial environment. The dominant cation in the catchment was $*Ca^{2+}$, with $*SO_4^{2-}$ and HCO_3^- dominating the anion solute load. The key weathering processes within Kårsavagge are therefore related to the dissolution of carbonates and sulphate minerals. These are the predominant sources of solutes in many glaciated environments due to their abundance and chemical reactivates (Tranter *et al.*, 1993a; Anderson *et al.*, 1997). High C-ratios are common in glacierized environments, illustrating the predominance of simple

carbonate dissolution or acid hydrolysis over the 2 step coupled pyrite oxidation driving dissolution of carbonate (SO-CD) (Fairchild *et al.*, 1994; Hodson *et al.*, 2000; Brown, 2002). C-ratios from the main channel in this investigation are generally around 0.5 indicating that the weathering of sulphate minerals plays a significant part in weathering reactions in this system, indeed in some instances SO_4^{2-} concentrations exceed that predicted by the SO-CD reaction couplet. The majority of the coupled pyrite-carbonate reactions are restricted to recently exposed rock surfaces and rock flour in subglacial drainage systems as pyrite oxidation occurs very rapidly and goes to completion in the presence of oxidizing agents (Moses *et al.*, 1987). As a result it is not unexpected for K1 to display a strong SO_4^{2-} signal in its hydrochemistry, and indeed the highest $*SO_4^{2-}$ concentrations occurred in K1 morning samples. However the high SO_4^{2-} excess observed on several occasions necessitates explanation.

Possible sources of this excess $*SO_4^{2-}$ are: (1) underestimates of atmospheric inputs, (2) Pyrite concentration exceeding that of calcite, leading to cation exchange with silicates or (3) the dissolution of gypsum. (1) is unlikely as there is a trend of increasing $*SO_4^{2-}$ concentration with the progression of the melt season, rather than the decrease observed in the Cl- concentration. (2) can be discounted due to the stoichiometry. SO-CD produces ueql1- ratios of 2:1:1 for $*Ca^{2+}$:$*SO_4^{2-}$:$*HCO_3^-$, $* SO_4^{2-}$ associated with ion exchange of silicate minerals also yields ratios of 2:1, as a result if all the $* SO_4^{2-}$ was sourced from oxidation reactions there would be a $(Ca^{2+} + Mg^{2+})$:SO_4^{2-} of 2:1. The observed ratio at K1 was 1.5 $(Ca^{2+} + Mg^{2+})$: 1 $* SO_4^{2-}$ which is consistent with a mix of SO-CD and simple gypsum dissolution. The dissolution of Gypsum displays 1:1 stoichiometry. Although gypsum has not been observed to provide a major source of SO_4^{2-} in many glaciated systems, the potential of evaporates to influence bulk hydrochemistry was suggested by

Tranter (1993a) and a similar combination of pyrite and gypsum sources for SO_4^{2-} has been observed in Karkevagge, another glacierized catchment in the same locality (Campbell *et al.*, 2001a; Darmody *et al.*, 2000; 2007). The occurrence of gypsum at the top site brings into question the assumption that Cl^- is solely of atmospheric origin as the occurrence of one evaporite increases the chances of others being present. However, given the behaviour of Cl^- over the melt season it is unlikely that a significant concentration was sourced from Halite (Hodgkins *et al.*, 1997).

C-ratios of around 0.5 are retained at most sites suggesting that SO-CD reactions remain the dominant source of solutes even downstream. This finding calls into question the assumption that SO_4^{2-} is sourced solely from the distributed system subglacially (Tranter *et al.*, 1993b). Although SO-CD dominates the weathering regime in the valley floor of the proglaical zone, the C-ratios of hill-slope groundwater samples are much closer to unity illustrating that other reactions such as carbonation or simple carbonate dissolution are dominant on the valley slopes. Inputs from these hill-slope groundwaters account for the relative increase in concentrations of $Ca^{2+} + Mg^{2+}$ relative to SO_4^{2-} downstream.

The interaction of these different sources is highlighted within the braided section below K1 (site closest to the glacier) where waters from defined flow paths interact to produce a matrix of source water combinations. Within the braids, there appeared to be 4 types of water sources: (1) glacial sourced with low C-ratios and high SO_4^{2-}, (2) snowmelt with reduced solute concentrations, (3) hill- slope ground-waters with high Si and C-ratios close to unity and (4) ground-waters routed through glacial moraine and forced to the surface by local topography with high Si concentrations but glacial SO_4^{2-} concentrations. The consequent inter site hydrochemical variability relative to the dominant water 'types'

is illustrated in Figure 11. The heterogeneous nature of proglacial zone hydrochemistry has been illustrated by several authors (e.g. Fairchild *et al.*, 1999b; Malard *et al.*, 1999; Beylich *et al.*, 2004; Robinson and Matthaei 2007), however, the variation shown in Kårsavagge over such a small area further highlights habitat heterogeneity, even relatively close to a glacial source. Solute concentrations at K8, where C-ratios fall suggest SO_4^{2-} acquisition from another source of gypsum.

Closed system low $p(CO_2)$ weathering occurred at the top site where the highly reactive sediments came into contact with very dilute melt water (Anderson, 2005) (Figure 6.2). Given that K1 was 0.13 km from the glacier snout, and the relatively fast rate at which CO_2 equilibrates, the CO2 deficit under the glacier $p(CO_2)$ was sufficient to maintain itself at least to K1. Below this top site mean $p(CO_2)$ has equilibrated itself with the atmospheric level. The occasional rises in $p(CO_2)$ can be attributed to microbial activity in the active layer (Hodson *et al.*, 2002b) as evidenced by the peak at K8 (a site in the lower catchment). Low $p(CO_2)$ conditions are often associated with calcite saturation (Sharp *et al.*, 1995b; Fairchild *et al.*, 1999a) however, this was not encountered at any site in Kårsavagge. The least negative values of calcite saturation were found in hill slope groundwaters which are sourced through calcite rocks and K6, which is assumed to derive a large proportion of its flow from draining these hill slopes.

6.5. iii) **Water source dynamics**

Despite the highlighted deviation from the assumed model of solute acquisition illustrated earlier with the possibility that pyrite oxidation occurred within certain areas of the proglacial terrain, the application of a hydrochemical mixing model appeared to

demonstrate the variation of contribution from various conceptual water sources. The majority of SO_4^{2-} still appears to have a distributed glacial origin, even this distributed flow path extends beyond the glacial terminus. The stark contrast between these distributed waters and fast routed, channelized meltwaters as illustrated by the diurnal pattern in solute concentrations. Finally, silica concentration also distinguishes between those flow paths with higher residence times.

Although results from 2008 are tentative, patterns of proportion of flow contribution were similar across both years, and reflect to an extent the seasonal water source progressions observed in other glacierized regions (i.e. early season snowmelt, followed by mid season glacier melt, late season groundwater dominated periods). However, a high proportion of these models were formulated in mid-latitude alpine environments with a relatively long melt season (e.g. Malard *et al.*, 1999; Hannah and Gurnell, 2001; Brown *et al.*, 2006d). The seasonal progression in this Arctic system does not appear to move to the groundwater dominated phase of the melt observed at these lower latitudes. Water source contributions at the top three sampling sites in Kårsavagge progresses from very early season distributed flow dominance (potentially an artefact of the model misinterpreting the sulphate pulse from snowmelt) rapidly to quick-flow dominance with occasional peaks in distributed flow. By mid melt season there was a gradual decrease in the proportion of quick-flow and an associated increase in distributed flow. The initiation in the quick-flow proportion reduction started earlier in 2008 than 2009, associated with warmer climatic conditions.

The seasonal transition in proportion of water contributed by ground waters was not concordant between years. Although groundwater contribution rarely rose above 20% at

any site on either year, the faster recession of quick-flow proportions observed in 2008 were associated with a gradual increase in proportion of groundwater at K2 and K3, suggesting that the melt season progressed further along the idealised glacier melt model than in 2009. The lack of increase in groundwater proportion at K1 may relate to the shorter melt season at this altitude, but more likely due to limited connectivity between stream and ground waters at this point.

Proportions at the lower sites (K6, K8 and K9) reflect a much larger system than the top three sampling sites and as such display patterns occasionally deviate. As the mixing model is based in solute provenance in the head of the basin there may be sources of solutes that it does not account for. As a result interpretations of the proportions model at these sites have to be tentative. Despite these caveats the lower sites do appear to display much greater proportional variability in 2008 than in 2009, reflecting the early recession of quick flow observed at the upper sites. The much greater proportion of flows provided by groundwater at K8 and K9 in 2008 also appears significant and highlights the inter annual variability in flow path often observed in glacierized catchments (Smith *et al.*, 2001). The lack of variability in water source contributions at K6 can be related to its proximity to the lake which mediates shorter term trends (Hieber *et al.*, 2002).

The mixing model enables the identification of water 'types' around the catchment and this will be used in later chapters to help explain distribution of invertebrate and fish communities. It is clear from the ternary plots that within the catchment, both in the upper and lower braided sections there are a significant number of different types of water, which creates a high variability of habitats that can be exploited.

Current processes governing main channel conditions in Kårsavagge are dominated by snow and glacial meltwater dynamics, much more so than other systems where groundwater plays a significant role at least for part of the melt season (Malard *et al.*, 1999; Brown *et al.,* 2006d). This is due to the catchments later spring thaw and early freeze up, and probably also to the rate of glacial melt. However, different processes govern smaller feeder streams, or at least they are less dominated by the glacial signal and the identification of this lateral variability is important in assessing how catchments such as this will respond to climatic variability.

6.6 Conclusions

Reflecting back to the aims of the chapter analysis of the Kårsavagge hydrochemistry has highlighted the temporal and spatial variations in water source dynamics, both longitudinally (along the main river channel) but also laterally (within two braided sections). The seasonal evolution of water source dynamics in Kårsavagge diverge from those observed in lower latitude glacierized systems, not incorporating a groundwater dominated phase.

1) Bulk meltwater chemistry in Kårsavagge is dominated by coupled sulphide oxidation carbonate dissolution reactions, with localized inputs from simple dissolution of sulphates (presumed to be gypsum) and carbonation of calcites.

2) A conceptual water source model incorporating quick-flow, distributed flow and groundwater sources can be applied to the water chemistry regime of Kårsavagge at least

for the top three sites (K1, K2 and K4). It would appear that the lower sites (K6, K8 and K9) may respond to different hydrochemical drivers.

3) The main channel in the upper reaches of Kårsavagge is dominated by the interaction of water from solute poor quick-flow sources and a more concentrated distributed flow source. Although there are short-term fluctuations in relative proportions from each source related to diurnal patterns in ablation and weather events; there is a general pattern of initial quick-flow dominance followed by gradually increasing distributed flow proportions as a sub-glacial channelized system forms. Away from the main channel there are many smaller channels in the upper and lower braids which display markedly different hydrochemical signatures. These reflect a variety of combinations of the main water sources and. may play an important role in the habitat heterogeneity around the whole of the Kårsavagge.

Chapter 7 - Spatial and Temporal Variation among Macroinvertebrate Communities within Kårsavagge

7.1 Introduction

Whether or not the Anthropocene (Crutzen, 2002) becomes an accepted epoch of geologic time, it is clear that human influence on the structure and functioning of natural global systems has been extensive. Perhaps the most pressing anthropogenic influence is that of climate change. Evidence of global warming is manifold (e.g. Overland, 2006; Turner *et al.*, 2007); average temperatures have steadily increased since 1850 with the rate of increase elevated to 0.177°C per decade since 1979 (IPCC, 2007b). This trend is predicted to continue with average global air temperatures forecast to rise by between 1.8 - 4.0 °C by 2100 (IPCC, 2007b). These average increases mask significant latitudinal variation. Polar amplification is expected to result in high latitudes exceeding global average warming (Holland and Bitz, 2003; Mcguire *et al.*, 2006; Serreze and Francis, 2006) with Arctic surface temperatures at 2100 predicted to rise by 4 -7 °C (ACIA, 2004). The reduction in the extent and thickness of Arctic sea ice (Overland, 2006), worldwide reduction in glacier mass balance (Dyurgerov, 2003; Meier *et al.*, 2003) and reduction in the extent of snow cover (Overland *et al.*, 2004) is associated with the recent warming trend. Zemp *et al.* (2006) predict a warming of 3 °C would result in the loss of 80% of alpine glaciers. If global warming proceeds as forecast over the next 100 years similar or greater reductions could be expected in other glaciated regions, including the Arctic.

Northern progression of range boundaries for some northern hemisphere species has already been observed (Warren *et al.*, 2001; Walther *et al.*, 2002; Parmesan and Yohe, 2003; Hickling *et al.*, 2006), and this, combined with shrinking habitat envelopes is putting stress on Arctic communities. The reason for monitoring high latitude communities with respect to climate change is twofold. Firstly, the rate of change at high latitudes necessitates a rapid assessment of how communities in these environments are structured and the identification of key parameters relating to their function. This will allow more informed assessments of the capacity of high latitude communities to react to predicted changes in climate and any associated shifts in seasonality/ ecological pressures'. Secondly, these remote areas allow us to track the signal of global warming with less interference from other anthropogenic forcing factors such habitat loss.

7.1. i) **Arctic streams and climate change**

Spring thaw in the Arctic is occurring earlier (Magnuson *et al.*, 2000; Stone *et al.*, 2002; ACIA, 2004), winter precipitation in many Arctic regions is increasing (Frey and Smith, 2003; Jonsson *et al.*, 2010) and there is predicted to be a steadily increase in the proportion of this that falls as rain (ACIA, 2004). These shifts in atmospheric water source dynamics, combined with the noted decline in global glacier volumes (Dyurgerov, 2003; Meier *et al.*, 2003; Zemp *et al.*, 2006) have implications for both the physical and chemical conditions within arctic freshwater systems (Wrona *et al.*, 2006; Milner *et al.*, 2009). The dependence of Arctic and Alpine streams on these shifting cryospheric sources makes them ideal systems for use in monitoring the impact of global warming at local, regional and global scales (Milner *et al.*, 2001a; Robinson *et al.*, 2007). Milner *et*

al., (2006) noted changes in persistence of stream communities associated with winter snow depth in Denali National Park and there are clear links between macro invertebrate taxa and the proportion of water from glacial sources feeding alpine streams (Brown *et al.*, 2006d). In order to monitor changes in stream systems appropriately, interpret the evolution of associated communities and predict the trajectory of future developments an accurate assessment of how contemporary systems are structured and function is essential.

7.1. ii) **Key environmental factors structuring communities in Arctic streams**

Ward (1994) identified three main alpine stream types based on a combination of thermal regime and water source. Kryal streams, divided into meta-kryal (0-2 °C) and hypo-kryal (2-4°C) are sourced from glacial meltwater and characterised by maximum temperatures not exceeding 4°C , deil flow fluctuations and varying turbidities. Rhithral streams have maximum temperatures ranging from 0- 10°C are variable in terms of temperature and flow due to a high influence of snowmelt. Krenal streams are sourced from groundwater, exhibit thermal and flow constancy, the so called 'summer-cool, winter-warm' habitat (Ward, 1985). Categorisation of alpine streams has been developed further by Brown *et al.*, (2003) and Brown *et al.*, (2009) who advocate the use of proportional water source contribution to describe a greater range of observed habitat heterogeneity, incorporating temperature, bed stability and flow variability. As these categories are based on water source and temperature they can be readily applied to any habitat where cold water streams occur.

The extreme seasonality and harsh conditions prevalent within most Arctic and Alpine streams define a major habitat filter (Hieber *et al.*, 2005) and as a consequence there is a sharp reduction in species richness and diversity with altitude and latitude (Stevens, 1992; Ormerod *et al.*, 1994; Lods-Crozet *et al.*, 2001b).

a) Harshness

Arctic and Alpine glacial stream ecosystems are characterized by low diversity communities structured along gradients of environmental harshness (Ward, 1994; Milner *et al.*, 2001a). The downstream evolution of the main channel habitat is well documented, as atmospheric interaction, tributary and groundwater inputs, lake storage and increasing terrestrial connectivity act to ameliorate conditions (Uehlinger *et al.*, 2003; Brown *et al.*, 2006a; Cadbury *et al.*, 2008; Finn *et al.*, 2010). These changes in within stream physico-chemical conditions are associated with a gradual turnover in the macrobenthic community (Giaslason *et al.*, 2001; Lods-Crozet *et al.*, 2001a; Milner *et al.*, 2001a; Milner *et al.*, 2008). As well as the much studied longitudinal gradients often associated with riverine ecology (e.g. Vannote *et al.*, 1980; Elwood *et al.*, 1983; Caissie, 2006) several authors have highlighted the extent to which lateral gradients exist and the role they play in maintaining local and regional biodiversity (e.g. Junk *et al.*, 1989; Ward, 1989). Recently lateral connectivity within glacial river systems and its influence on macroinvertebrate diversity has received greater interest (Brunke *et al.*, 2003; Arscott *et al.*, 2005; Malard *et al.*, 2006; Hannah and Brown, 2008), with the greater habitat heterogeneity it provides elevating local biodiversity above that observed in the main channel (Arscott *et al.*, 2005; Brown, 2007).

b) Temperature

Glacier-fed streams are characterised by year-round low temperatures limiting primary production and inhibiting rapid growth (Steffan, 1971; Ward, 1994a; Lencioni, 2004). Despite some streams retaining flow even in winter due to ground water inputs (Irons *et al.*, 1993; Burgherr and Ward, 2001), this is not the case for all (Olsson, 1981) and macroinvertebrate communities are typically limited to cold stenothermic species. Specific adaptations include melanism (Downes, 1965), diapause (Økland, 1991), freeze avoidance (Irons *et al.*, 1993), freeze resistance (Bouchard *et al.*, 2006), freeze tolerance (Olsson, 1981) and merovoltine life cycles (Butler, 1982). Many taxa from cold environments display a range of phenotypic and behavioural plasticity to account for the variety of challenges posed by the environment (for thorough reviews see Downes, 1965; Danks, 2007; Lencioni, 2004).

c) Flow variability

The classic annual hydrograph in glacial streams moves from very high discharges associated with spring snowmelt to flows consisting primarily of ice-melt through summer, which recharges groundwater supplies that continue to provide flows later in the melt season (Smith *et al.*, 2001). Overlaid on top of this seasonal pattern are diel fluctuations in discharge associated with fluctuations in received solar radiation (Ward, 1994; Hannah and Gurnell, 2001; Füreder *et al.*, 2001) which also leads to diel water temperature variability (Brown *et al.*, 2006b). Diurnal flow regimes, intense snowmelt flows and often rapid transport of rainfall into the main channel (ACIA, 2004) create a low stability environment, with a high incidence of bed movement (Milner *et al.*, 2001a;

Parker and Huryn, 2006). It has been suggested that increased stability in early spring before the onset of snowmelt and autumn when flows are dominated by groundwater provide 'windows of ecological opportunity' when organisms can exploit this otherwise hostile environment (Uehlinger *et al.*, 2010; Uehlinger *et al.*, 2002).

d) Suspended load

Glacial melt water has high and often unpredictable sediment loads, sometimes exceeding 2000 g L^{-1} (Gurnell, 1987). High sediment loads scour surfaces and backscatter light, greatly limiting potential primary productivity.

These strong forcing factors create deterministic communities within arctic and alpine streams constrained within narrow range by the harsh environment.

e) Benthic Habitat

Low temperatures, high flow variability, high and highly variable SCC and unstable substrates lead to low annual productivity of the benthic environment in Arctic and Alpine streams (Hieber *et al.*, 2001; Uehlinger *et al.*, 1998). However their latitudinal / altitudinal position and highly unstable channels mean that allochthonous inputs close to the glacier terminus are limited (Zah and Uehlinger, 2001). Particulate organic matter is available from glacial melt waters (Zah and Uehlinger, 2001; Tockner *et al.*, 2002) but the amount assimilated by kryal communities is negligible until channels stabilize downstream (Zah and Uehlinger, 2001; Füreder *et al.*, 2003). So despite the low average

primary productivity of glacial systems it is none the less autochthonous producers which form the base of glacial stream communities (Lavandier and Décamps, 1984; Suren, 1993; Zah *et al.*, 2001). As stream beds stabilize productivity increases along with the appearance of more complex plant and bryophyte communities (Suren, 1996; Hieber *et al.*, 2001). These play a role in increasing habitat complexity, reducing flows and trapping the limited allocthonous matter (Suren, 1993; Finlay and Bowden, 1994; Bowden, 1999; Chantha *et al.*, 2000; Lencioni and Rossaro, 2005). It is these functions, along with the increase in productivity that helps support a more diverse macroinvertebrate community further downstream from the source (Bowden, 1999; Lencioni and Rossaro, 2005). These more complex primary producers are far more susceptible to scour and disturbance than the diatom species that dominate close to the glacial source (Hieber *et al.*, 2001) so tend to be found attached to larger, more closely packed or more sheltered substrate particles, less likely to transported (scoured) during higher flows (Suren, 1993; 1996).

One of the key environmental influences structuring macroinvertebrate communities is the frequency of flow events likely to cause catastrophic drift (Death and Winterbourn 1994; Ward, 1994; Milner *et al.*, 1994; 2001, Snook *et al.*, 2001). However what constitutes catastrophic drift depends on the organism and the micro-habitat in which it exists (Barnes and Mann, 1991; Lencioni and Rossaro, 2005; Gibbins *et al.*, 2007). Small, multi-voltine species able to utilise small interstitial spaces as flow refugia or carryout their life cycle rapidly between predictable high flow events dominate glacial headwaters where lager bodied, uni- or semi-voltine species are rare (Strathdee and Bale, 1998; Hieber *et al.*, 2003; Danks, 2007). Benthic environments with higher habitat complexity

such as a diverse mix of substrate sizes including larger caliber stones resistant to scour which allow the development of attached vegetation/ biofilms (Suren, 1993; 1996) that help to bind substrate further enables a wider variety of species, including larger, longer lived taxa to cope with high flow events (Death and Winterbourn, 1994; Lencioni and Rossaro, 2005). Where stability is above a certain threshold it is substrate complexity rather than simply size that impacts community development. Large boulders on bedrock or sand grains provide few interstices for invertebrates to utilize or to trap detrital material from allothonous inputs (Lencioni and Rossaro, 2005; Duan *et al.*, 2008). A high diversity substrate in contrast allows the accumulation of particulates as well as sites for autochtonous production which supports a more diverse benthic community (Barnes and Mann, 1991; Death and Winterbourn, 1995; Lencioni and Rossaro, 2005).

7.1. iii) **Model of longitudinal community development**

Milner *et al.* (2001a) developed a conceptual model describing the evolution of community structure with respect to temperature and stability along an upstream-downstream gradient within a glacial stream in Denali National Park, Alaska. The model predicts a community comprising solely of Diamesinae chironomidae where temperatures don't rise above 2°C (T^{max} of 2°C) with low stability substrate. As water temperatures, bed stability and allocthonous inputs increase further from the glacial source community diversity increases. First, Orthocladiinae then Tipulidae and Oligochaeta colonize; as harsh habitat conditions continue to ameliorate, Simuliidae and Empididae (dipterans), Baetidae (mayflies), and Perlodidae and Taeniopterygidae (stoneflies) will potentially colonise. Further downstream, conditions allow Limnephilidae and Rhyacophilidae

(caddisflies), Chironominae (Chironomidae), Nemouridae and Leuctridae (stoneflies) and Heptageniidae (mayflies) to be become part of the community. This model has been tested many times and is generally found to be robust given modifications for the local species pool (Milner *et al.*, 2001b; Hieber *et al.*, 2005; Jacobsen *et al.*, 2010).

The downstream diversity of a glacier-fed stream community can be influenced by various channel modifiers (Milner *et al.*, 2001a) similar to the discontinuities proposed by Ward and Stanford (1983). Pro-glacial lakes act to dampen diel variability, reduce turbidity and increase water temperature (Hieber *et al.*, 2002; 2005; Uehlinger *et al.*, 2003; Jacobsen *et al.*, 2010; Finn *et al.*, 2010) and tributary inputs can modify main channel conditions negatively or positively depending on their source (Brittain *et al.*, 2001; Brown *et al.*, 2007).

7.1. iv) **The lateral and temporal dimension of stream systems**

Despite the harsh conditions, and low diversity communities generally associated with glacial streams close to their source, proglacial floodplains form a complex matrix of habitats that can incorporate a range of thermal, chemical, turbidity and stability conditions (Ward *et al.*, 1999; Brown *et al.*, 2006a; Uehlinger *et al.*, 2003; Malard *et al.*, 2006; Robinson and Matthaei, 2007). This habitat heterogeneity increases local biodiversity, as taxa excluded from the main channel during phases of intense melt are able to maintain viable populations in rhithral, krenal or seasonally connected channels as well as taxa that occur only in specific patch types (Brunke *et al.*, 2003; Arscott *et al.*, 2005; Brown *et al.*, 2006d). Lateral and vertical connectivity varies seasonally with

system expansion and contraction (Malard *et al.*, 2006; Doering *et al.*, 2007) adding a temporal dimension to local biodiversity gradients. Indeed, biodiversity within glacial systems is a function of seasonality. Although beta diversity can be high during times of peak glacial influence, when the glacial signal reduces and conditions within the main channel attenuate, cold stenothermic taxa not associated with the kryal biotope can be found close to the glacier snout, despite the maintenance of a kryal thermal regime (Burgherr and Ward, 2001). The implication is that stability and/or turbidity associated with glacial input structures the typical kryl community that is a subset of a local biota, which are all cold stenotherms to some degree. The extent and duration of these 'ecological windows' (Uehlinger *et al.*, 2002) will vary with geomorphology and latitude. For example ecological windows in Arctic glacial streams, without significant groundwater input, that undergo rapid freeze up, are not likely to be very long lived.

Braiding is a common feature in glacial catchments as streams often flow through regions of recently deposited unconsolidated material (Gurnell *et al.*, 2000). These braided regions have high habitat turnover (Arscott *et al.*, 2002) which aligned with the complex nature of the floodplain makes for a highly patchy environment containing habitats that seasonally, occasionally or never (as yet) display a glacial signal. As such, communities which represent a cross-section of time since glacial influence may be present laterally.

Species interactions also play a role in structuring glacier-fed stream macroinvertebrate assemblages. Flory and Milner (1999) illustrated that *Diamesa lupus* densities reduced as a result of interference from other chironomid competitors. This suggestion, that at least some metakryal species are fugitives confined not only to cold, but also highly unstable habitats identifies glacier-fed streams close to their snouts as shifting fronts of

colonisation. Local diversity is maintained as long as the glaciers undergo periodic expansion and contraction, maintaining spatial and temporal gradients of disturbance which these cold stenothermic fugitives can utilize.

7.2 This study

The majority of work on glacial stream structure and function has been carried out in temperate alpine zones such as the Swiss Alps (e.g.Ward *et al.*, 1999; Finn *et al.*, 2010) or the French Pyrenees (e.g. Snook and Milner, 2001; Brown *et al.*, 2006d;) or on continental North America (e.g. Flory and Milner, 1999; Milner and Robertson, 2010). To date there has been limited published work on the ecohydrology within glaciated streams in the Arctic (but see Friberg *et al.*, 2001; Lods-Crozet *et al.*, 2001b; Lods-Crozet *et al.*, 2007; Woodward *et al.*, 2010). Glacial streams in the Arctic are subject to 24 hr daylight in summer and 24 hr darkness in winter, they can extend to low altitudes and flow through catchments containing permafrost (ACIA, 2004). This heightened seasonality, combined with reduced species richness towards the poles (Lods-Crozet *et al.*, 2001b) may result in Arctic glacial streams functioning differently to their alpine counterparts; resulting in divergent responses to climate change. The Arctic Climate Impact Assessment (ACIA, 2004) highlighted Arctic freshwater systems and their potential response to current and predicted Arctic warming as a major gap in understanding. This study investigates the spatial and temporal distribution of macroinvertebrates within a glaciated catchment in Swedish Lappland in relation to environmental variables. The overarching aim is to extend knowledge regarding this complex and under threat Arctic ecosystem. With this in mind the chapter objectives were to:

1) Identify the macroinvertebrate community of Kårsavagge and identify key environmental variables which structure this community.

2) Compare macroinvertebrate richness and diversity longitudinally down the main channel of the Kårsa River with that found laterally within the upper braided section to assess the extent lateral habitats contribute to wholes system diversity.

3) Compare functional feeding groups of macroinvertebrates found at each sample site to elucidate how they change with respect to dominant water source and position in the catchment.

4) Assess the vulnerability of these communities to predicted climate change.

7.3 Methodology

7.3. i) **Macroinvertebrate collection**

On each sampling occasion five replicate 0.1 m^2 Surber samples (250 μm mesh) were collected randomly from within a 15m reach. The benthos was disturbed for one minute and any material entering the flow was collected in the surber net. The material collected from each replicate was stored separately in 70% ethanol. Benthic macroinvertebrate sampling of the main channel sites (K1, K2, K4, K6, K8 and K9) was carried out once a fortnight in both 2008 and 2009. In 2009 sites within the upper braided section (Sites

labelled B) were sampled at least once with key channels sampled on two occasions. This followed exploratory kick samples across the upper braided section in 2008.

7.3. ii) **Physico-chemical habitat variables (based on data from 2009)**

One way ANOVA's were carried out to test for significant differences in physico-chemical habitat variables between sites where invertebrates were sampled (K1, K2, K4, K6, K7 and K9). This included Chlorophyll a concentration, dissolved ion concentrations, velocity and suspended sediment concentration; differences were considered significant when $P < 0.05$.

Repeated measures reflecting the benthic habitat such as Chlorophyll a concentration (from algal samples), percentage moss cover, dissolved ion concentration, velocity and suspended sediment concentration were reduced down to give one average score for each site to be used within further analysis. The rationale behind this is decision was that despite the high temporal variability of some of these parameters (e.g. SCC) the time scale over which vary is less than the life span of the macroinvertebrates being investigated so the average value is a more appropriate descriptor of habitat conditions than a point in time sample. Maximum and minimum recorded values/ concentrations were also included in the analysis to investigate whether threshold tolerance values were important in macroinvertebrate distribution. Temperature was treated in the same way except that degree day counts (see Chapter 4) an ecologically important variable were computed and used in the analysis.

Benthic habitat descriptors such as pfankuck bed index score, sediment size (D50), bed roughness, sediment diversity and gradient that were taken once seasonally at each site were put straight into the RDA model.

7.3. iii) **Macroinvertebrate sorting, identification and analysis**

Each individual surber sample replicate (5 per site for each sample date) was sorted using a light microscope (x10 magnification) and organisms stored in 70% ethanol to await identification. This study deals only with invertebrate larvae, all pupae or adults were not included in the following analysis. Identification data from each replicate was then pooled to avoid variation due to small scale impacts to give one abundance value per site per date (Brown *et al.,* 2006d). Keys used for identification were: Chironomidae of the Holarctic region: keys and diagnoses (Wiederholm, 1993); Aquatic Insects of Northern Europe Vol. 1. & 2 (Nilsson, 1998); A Key to the Case-bearing Caddis Larvae of Britain and Ireland (Wallace *et al*., 2000); A revised key to the caseless caddis larvae of the British Isles with notes on their ecology, (Edington and Hildrew, 1995) and A Key to the Adults and Nymphs of the British Stoneflies (Plecoptera): With Notes on Their Ecology and Distribution (Hynes, 1995).

Non Chironomidae taxa were identified under a Zeiss Stemi-2000 stereo-microscope (6-50x magnification) and where ever possible Ephemeroptera, Plecoptera, Trichoptera were identified to species; most other taxa could only be taken as far as genus/ family.

The vegan (Oksanen *et al.*, 2011) package in R (R_Development_Core_Team, 2011) was used to calculate the following diversity indices: richness (*R*), Simpsons diversity (D1) and Pielou's evenness (*E*).

Data from 2009 was used to investigate whether the observed differences in taxa between sites reflected a shift in macroinvertebrate community function or simply the replacement of one taxa by another using the same resource. Taxa were assigned to a functional feeding group based on their food preferences. The classification of feeding guild was based on the work by the STAR group (Bis and Usseglio-Polatera, 2004) who used autoecological data gathered from a very large and scattered published expert knowledge and diverse literature sources' to produce a table of taxa traits and habitat preferences, including food preferences (for full methodology see Bis and Usseglio-Polatera, 2004). This was cross-referenced with data on feeding guilds presented in Tachet *et al.*, (2000) to ensure classification was done as accurately as possible. Feeding guilds used were: Deposit feeder, Shredder, Scraper, Filter feeder, Piercer, Predator or undefined. The undefined category was used when no information was available on taxa's feeding preferences. All individuals collected at each site were pooled for this analysis.

Taxa abundance was log 10 $^{(x+1)}$ transformed and Bray-Curtis distances between samples computed. Non-metric Multi Dimensional Scaling (NMDS) was used to visualize spatial and temporal variations within macroinvertebrate communities and a stress value calculated to assess the fit between the ordination and the original distance matrix (Venables and Ripley, 2002; Oksanen *et al.*, 2011). For each analysis an iterative procedure (1200 iterations) with variable starting conditions was used to find the configuration with the lowest stress value and avoid local minima.

Hierarchical cluster analysis using Wards Minimum variance method on the Bray-Curtis distance matrix was used to investigate clustering between samples at the different sites in the 2009 data. The optimum number of clusters was identified using the partition around mediods (pam) clustering algorithm (Maechler *et al.*, 2005). Redundancy analysis (RDA) and partial RDA were used to investigate the relationships between individual taxa and physico-chemical habitat variables. Raw taxa abundances were Hellinger transformed prior to analysis to avoid the horseshoe effect (Zuur *et al.*, 2007).

Dominance/ Diversity of different sampled communities were investigated by fitting Rank Abundance Models to the data. Akaike's AIC was used to discriminated between the fit of different models (Oksanen *et al.*, 2011). Models tested were; broken stick, geometric series, log-normal, Zipf and Zipf-Mandelbrot (for detailed explanations see Bastow, 1991).

7.4 Results

Over both years a total of 395 benthic samples were collected, sorted and identified yielding 92 taxa / morphotypes (See appendix A). All communities sampled within Kårsa valley over both years were dominated by Chironomidae, comprising 74% of all individuals encountered. The remaining 26% was split between 33 families; the largest non Chironomidae contributions were made by Baetidae (9.5%), Simuliidae (3.8%), Perlodidae (2.9%), Limnephilidae (1.7%), Leuctridae (1.5%) and Limoniidae (1.1%). Identification of Chironomidae in 2008 samples was only to family whereas in 2009 it was down to genus/morphotypes. For this reason the initial analysis focuses on the lower

resolution of bi- yearly data and then subsequent sections analyze the higher resolution 2009 data. Other groups were taken to genus.

7.4. i) **Physico-chemical parameters along the main channel**

The six longitudinal sites displayed a variety of physico-chemical habitat conditions. Average water temperature increased from K1 to K9 and an ANOVA with post hock TUKEY test separated the six sites into 4 significantly different thermal clades namely K1; K2 & K4; K6 ; K8 &K9 (see Table 5.6, Table 5.7 and Figure 5.10).

There is also significant variation between the six sites along the main channel with respect to other physic-chemical parameters, suspended sediment concentration, conductivity, chloride concentration, resistivity as well as chlorophyll *a* concentration and % moss cover (See Table 7.1 for details of ANOVA, Table 7.2 and Figure 7.1). The Pfankuch Index and sediment diversity also illustrated strong longitudinal gradients (Table 7.2).

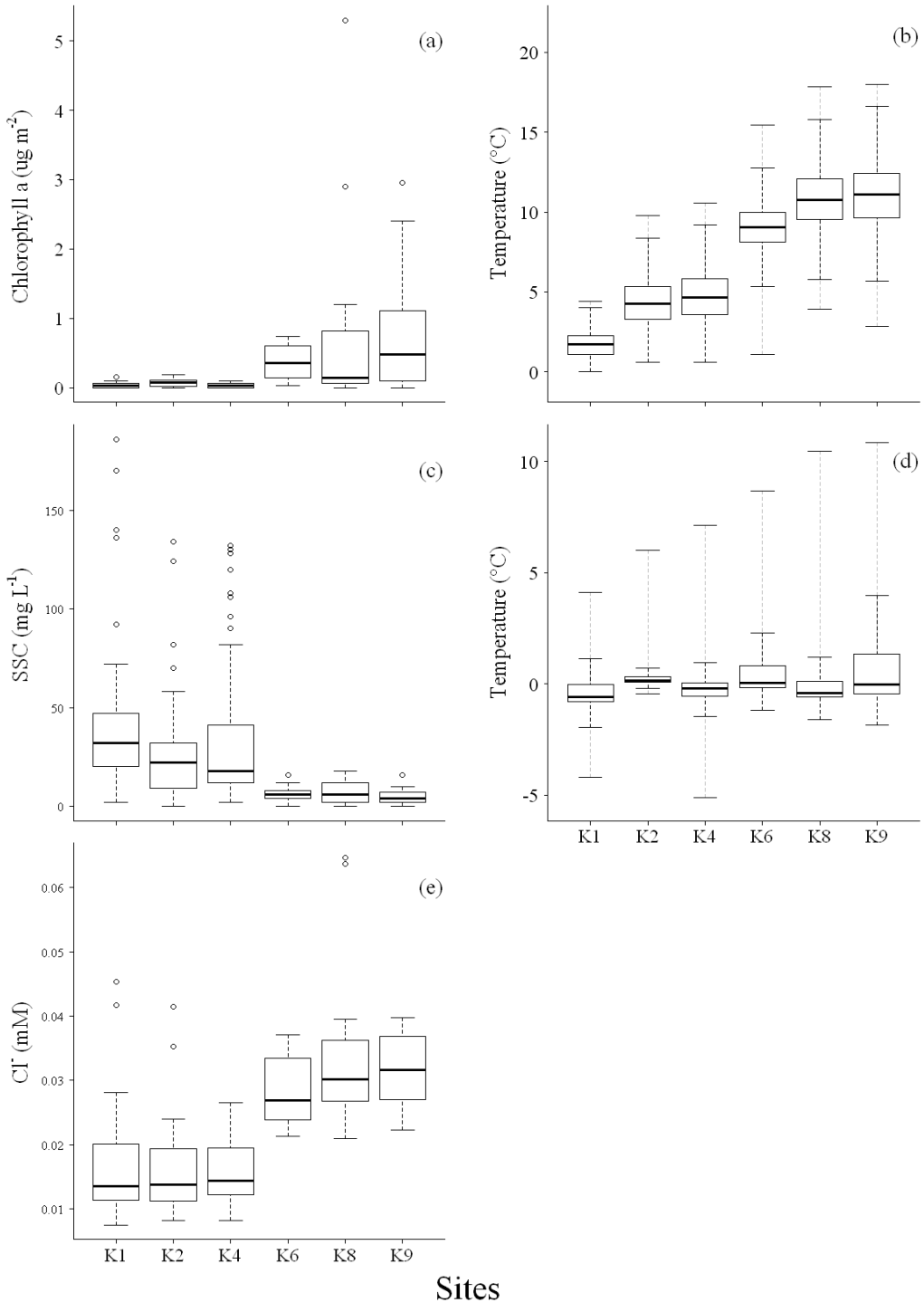

Figure 7.1- Boxplots comparing physiochemical habitat variables between the six main longitudinal sites along the Kårsa River. (a) Chlorophyll a concentration (data from 2009, n=11 for all sites). (b) Summer temperatures (data from 2008 and 2009). (c) Suspended sediment concentration (data from 2008 and 2009; K1 n = 43, K2 n = 56, K4 n = 99, K6 n = 12, K8 n = 24, K9 n = 23). (d) Annual temperatures monitored every 15 min (data from 2007-2009). (e) Chloride concentration from water samples (data from 2008 and 2009; K1 n = 46, K2 n = 44, K4 n = 44, K6 n = 21, K8 n = 21, K9 n = 20).

Table 7.1 – Summary table for the one way analysis of variance on a selection physico-chemical parameters measured at invertebrate sample sites across both 2008 and 2009 (K1, K2, K4, K6,K8 and K9). d.f. = degrees of freedom; SS = sum of squares; s^2 = estimated variance.

Cl^- concentration (mM)	**d.f.**	**SS**	**S^2**	**F-Value**	**P-Value**
Site	5	9.9x10-3	1.9x10-3	38.98	0.000
Residuals	185	9.4x10-3	5.12x10-5		
Total	190	$1.9x10^{-2}$			
SCC (mg L^{-1})	**d.f.**	**SS**	**S^2**	**F-Value**	**P-Value**
Site	5	41931	8386	9.55	0.000
Residuals	251	220488	878		
Total	256	262419			
Chlorophyll a (µgcm^{-2})	**d.f.**	**SS**	**S^2**	**F-Value**	**P-Value**
Site	5	9.08	1.82	2.81	0.024
Residuals	60	38.82	0.65		
Total	65	47.90			
% moss cover	**d.f.**	**SS**	**S^2**	**F-Value**	**P-Value**
Site	5	98086	19617	43.98	0.000
Residuals	227	101258	446		
Total	232	199344			
Resistivity (kohn)	**d.f.**	**SS**	**S^2**	**F-Value**	**P-Value**
Site	5	1242	248.39	4.90	0.000
Residuals	157	7967	50.75		
Total	162	9209			
Conductivity (µS)	**d.f.**	**SS**	**S^2**	**F-Value**	**P-Value**
Site	5	3716	743.2	2.63	0.025
Residuals	157	44344	282.4		
Total	162	48060			

Table 7.2 Temperature and physical characteristics of longitudinal sites within Kårsavagge. Pfankuck index of bed stability (Pfank), bed gradient (Grad), D50, Relative roughness (Rel R), Substrate diversity (Sub div), Conductivity (Cond), pH Total dissolved solids (TDS) resistivity (RES), Average temperature (Tav), minimum temperature,(T min), maximum temperature (Tmax), accumulated degree days (DD) and standard deviation of the temperature (Stdev). Values for both sampling (2008 and 2009) are provided.

Site	Pfank	Grad (%)	D50 (mm)	Rel R	Sub div	Cond (µS)		pH		TDS (mg L^{-1})		Res (kohn)		Temperature (over summer) (°C)									
														T Av		T Min		T Max		DD		Stdev	
						08	*09*	*08*	*09*	*08*	*09*	*08*	*09*	*08*	*09*	*08*	*09*	*08*	*09*	*08*	*09*	*08*	*09*
K1	51	4.3	70	0.74	0.82	41.0	32.4	7.19	7.67	27.7	21.8	28.8	31.8	1.65	1.67	0.00	-0.01	4.41	4.02	121.4	129.3	0.75	0.91
K2	36	9.1	65	1.05	0.82	45.1	37.4	7.23	7.31	30.2	25.9	22.7	26.7	4.27	4.41	0.57	0.70	9.77	9.04	317.7	339.2	1.59	1.56
K4	53	3.5	52	0.59	0.80	44.7	37.2	7.35	7.34	30.0	25.0	22.5	26.8	4.69	4.85	0.94	0.57	10.57	10.04	349.0	373.5	1.71	1.77
K6	19	0.8	98	0.75	0.75	40.9	38.1	7.36	7.51	26.9	25.4	23.7	24.9	8.75	9.26	1.07	3.74	13.75	15.47	651.4	719.7	1.94	1.88
K8	18	0.6	133	1.12	0.81	46.9	40.9	7.34	7.37	30.8	27.0	20.7	23.5	10.44	11.25	3.90	5.37	17.00	17.86	783.8	866.0	2.21	2.20
K9	21	0.4	105	0.88	0.80	49.3	44.3	7.42	7.76	32.2	29.1	19.6	24.0	10.07	11.63	2.84	5.85	17.13	18.01	775.4	895.5	2.46	2.04

7.4. ii) **Longitudinal community patterns**

Overall richness in the main channel sites was lower in 2009 than in 2008 with 47 taxa recorded in 2008 compared to 35 in 2009. The six longitudinal sampling sites can be split into two sets of three based on their taxa richness and diversity scores. Those upstream of the first lake (K1, K2, K4), are characterized by low richness, low diversity and low evenness scores. The three sites downstream of the first lake have much higher diversity and richness scores (Table 7.3).

Although there was a general pattern of increasing community diversity scores with distance of the site from source, it was not a linear relationship. K1, the closest site to the glacier snout supported 5 taxa in 2008 and only 3 in 2009. Richness at stream sites above the lake peaked at K2 with 15 taxa recorded in 2008 and 10 in 2009 before dropping to 9 and 6 at K4 in 2008 and 2009 respectively. Shannon diversity above the lake decreased with distance from source as a function of increased abundance but a subsequent reduction in evenness (Table 7.3).

There are different patterns in community score downstream of the lakes in both years. The highest richness recorded in 2008 (27) was found jointly at K6 and K8 with fewer (23) observed at K9. In contrast the 2009 data displayed a richness pattern of K9>K6>K8. Diversity scores below the lakes increased with distance downstream in all years.

Table 7.3 - Taxa richness (R), Simpsons diversity (D1) and Pielou's evenness (E) for macroinvertebrate sample sites within Kårsavagge (for distribution around the catchment see figures 3.1 and 3.2). *2009 data including Chironomidae identified down to genus.

Site	2008			2009			2009*			Total		
	R	D_1	*J*	*R*	D_1	*J*	*R*	D_1	*J*	*R*	D_1	*J*
K1	5	0.09	0.15	3	0.10	0.20	8	0.18	0.23	6	0.09	0.14
K2	14	0.05	0.07	9	0.03	0.04	17	0.38	0.30	18	0.04	0.06
K4	8	0.04	0.07	5	0.02	0.05	13	0.26	0.26	9	0.03	0.05
K6	27	0.48	0.38	19	0.33	0.30	32	0.88	0.73	29	0.43	0.34
K8	27	0.68	0.51	17	0.81	0.72	28	0.91	0.82	29	0.78	0.60
K9	23	0.81	0.66	22	0.84	0.71	37	0.89	0.76	26	0.83	0.68
B1	2	0.36	0.79	2	0.02	0.09	2	0.02	0.09	3	0.11	0.22
B2	2	0.22	0.54	1	0.00	0.00	3	0.17	0.34	2	0.08	0.25
B6	1	0.00	0.00	4	0.07	0.14	10	0.21	0.25	4	0.05	0.11
B7	4	0.33	0.47	2	0.03	0.12	4	0.13	0.22	5	0.16	0.25
B8	11	0.36	0.37	7	0.76	0.80	10	0.79	0.77	12	0.56	0.54
B9	6	0.46	0.52	5	0.60	0.76	7	0.82	0.94	9	0.64	0.62
B10	7	0.76	0.84	6	0.64	0.73	10	0.84	0.89	10	0.84	0.86
B12	-	-	-	10	0.14	0.17	20	0.75	0.61	-	-	-
B13	-	-	-	5	0.33	0.44	8	0.50	0.55	-	-	-
B14	-	-	-	13	0.18	0.20	21	0.78	0.61	-	-	-

Cluster analysis indicated a cone shaped cluster of samples towards the left hand side of the plot, close to the apex are subject to similar environmental constraints, which are lifted as you move further right resulting in greater variation in bray distance scores between biweekly samples (Figure 7.2 [stress = 0.17]).

Sites from the upper catchment (K1, K2 and K4) were plotted together, indication that environmental conditions at sites above the lake place constraints upon the main channel stream community. Despite this proximity there is a clear clustering of sites, with samples

from K1 at different dates found towards the far left of the agglomerate cluster and those of K2 further right. A seasonal trend is apparent as samples from both years taken early in the summer tend to be at the left of their respective cluster and move further right as the season progressed. K6, K8 and K9 also display seasonal trajectories, however with reduced environmental harshness, seasonality and variability are increased. Early season '08 samples were separate from early season '09 samples implying annual variability.

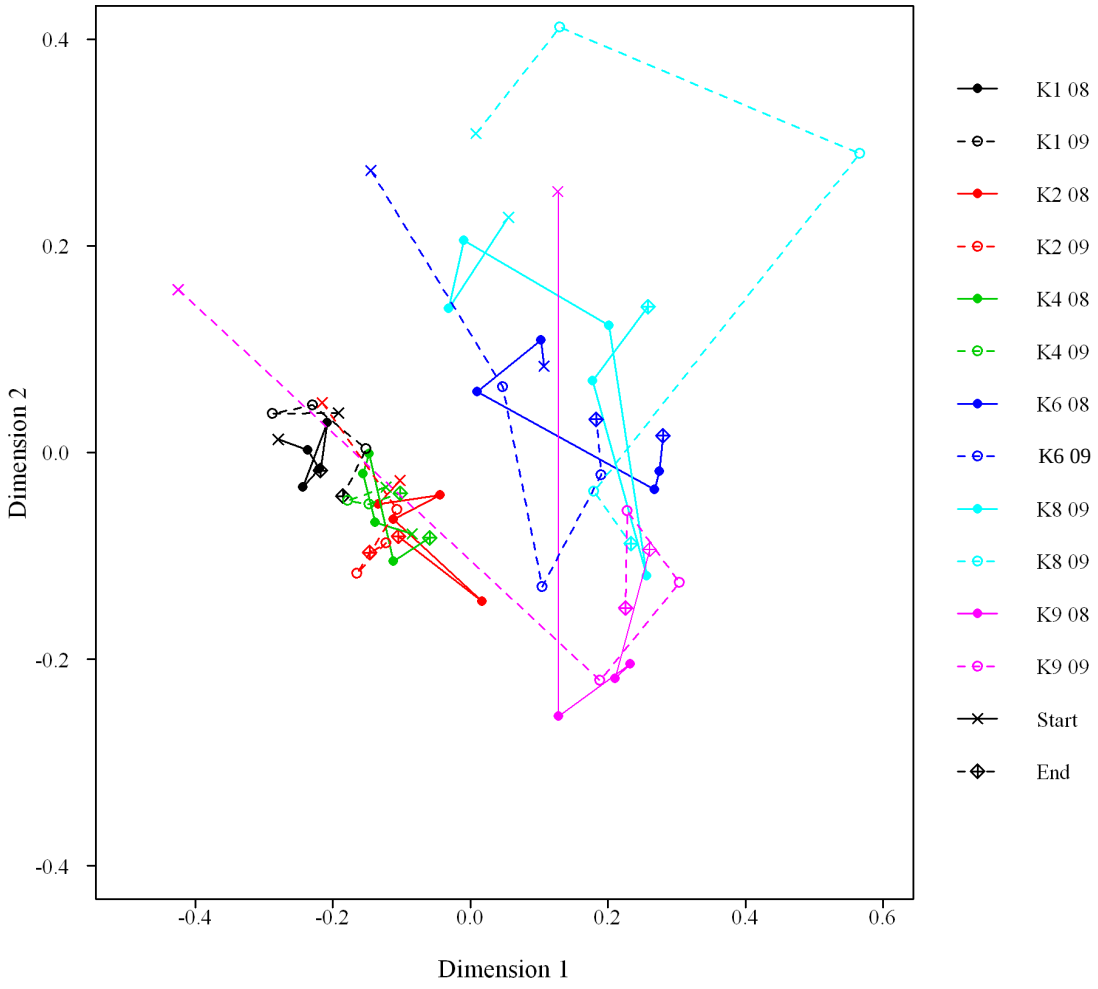

Figure 7.2 - NMDS plot based on Bray-Curtis distances of the trajectory taken by macroinverebrate communities at each of the main longitudinal sites within Kårsavagge in 2008 (—●—) and 2009 (– ● –). X signifies the earliest sampling point at any given site on either year, ◈ signifies the final sampling event for any given site on either year. Every sampling occasion is plotted. Stress = 0.17, 1200 iterations.

Chironomidae in the 2009 samples were identified down to genus/ morphotype and as a result more subtle shifts in taxa distribution were revealed. Richness scores increased with greater resolution but there is also a concomitant increase in Shannon diversity (Table 7.3). With this increased resolution of the Chironomidae, Shannon diversity increased with the distance from source, despite elevated abundances. K2 is the exception as it, rather than K4 supported the highest macroinvertebrate diversity at stream sites above the lakes.

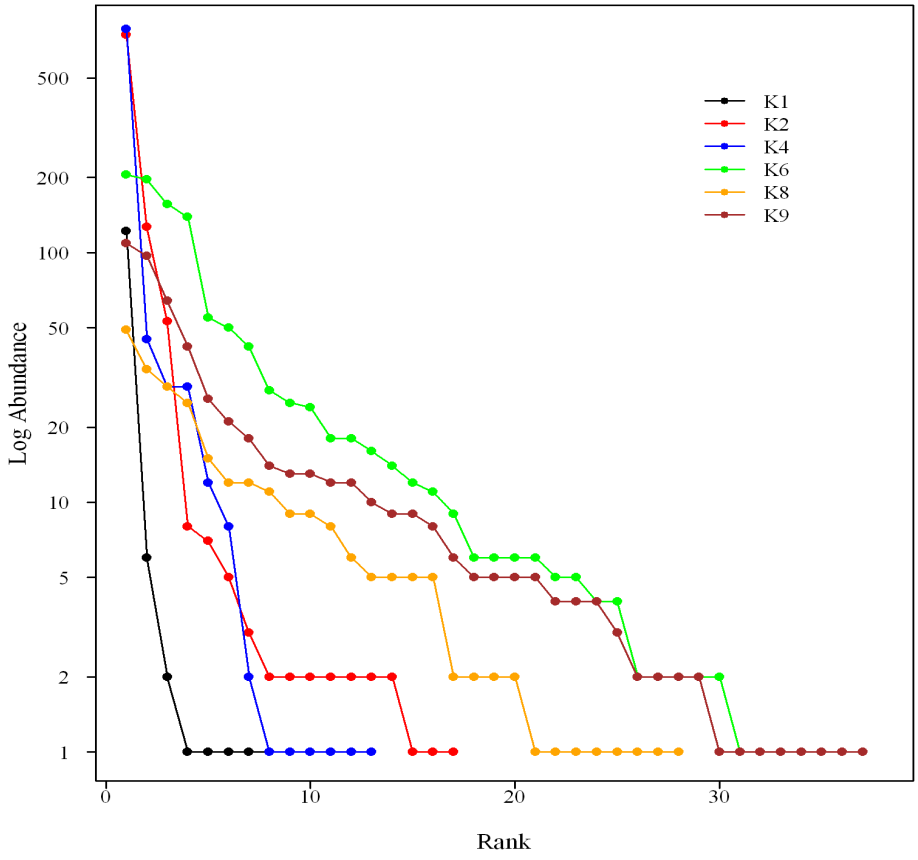

Figure 7.3 – Rank abundance plots for macroinvertebrate taxa encountered in samples taken in 2009 from the main longitudinal sites (K1, K2, K4, K6, K8 and K9). Data from each sampling event (n=5) have been pooled to produce one community for each site; Chironomidae have been identified down to genus.

Rank abundance plots (Figure 7.3) appear to show a shift from the dominance-pre-emption model, where successive species pre-empt a dominant (>50%) portion of remaining niche space (Begon *et al.*, 1996) to a more equitable dominance-decay model at the lower sites. Table 7.4 illustrates the goodness of fit for various rank abundance models to the cumulative abundance data for each site over the entire sampling season. The resource pre-emption does not supply the best fit for any of the sites in upper catchment. K1, K2 and K4 fit the Zipf model, whereas K6 and K9 fit the Zipf-Mandelbrot model (essentially the same - the difference being that the Zipf-Mandelbrot model incorporates a function dependant on niche diversity). These models assume that a species presence is based on 'costs' and are deterministic (Zipf more so). Once costs (such as environmental conditions or previous species presence) are met a species is likely to invade (Wilson, 1991). Costs are much higher for larger, late successional species, and low for pioneer species such as *diamesa spp*. The best fit for K8 is the geometrical series model, which assumes strong competition and resource pre-emption by dominant/ early arriving species (Table 7. 3).

Table 7.4 – Akaike's information criterion (AIC) score for assessing the fit of a rank-abundance model to data from macroinvertebrate samples taken in 2009 (data from each sampling date have been pooled and Chironomidae identified down to genus) from the main longitudinal sites (K1, K2, K4, K6, K8 and K9). The lower the score the better the fit of the model to the data.

Site	Akaike's AIC				
	Broken Stick	Geometric series	log-Normal	Zipf model	Zipf – Mandelbrot
K1	214.8	69.8	51.5	36.5	38.5
K2	1754.6	314.6	119.8	83.1	85.1
K4	1629.3	334.3	137.3	112.4	114.3
K6	518.8	225.0	271.4	369.1	187.1
K8	120.3	106.1	109.2	128.3	106.4
K9	289.9	205.8	166.7	192.6	156.3

7.4. iii) **Lateral community patterns**

Environmental conditions within the braided section are highly variable (Tables 7.5 and 7.6). This variation is due mainly to differences in dominant water source and channel aspect. Mean water temperature during the summer study period ranged from 2.77°C to 8.76 °C in 2008 and 3.11°C to 9.83°C in 2009. When compared to mean daily near bed temperatures along the length of the river over the same time periods, post hoc TUKEY groupings of ANOVA's on 2008 ($F_{19, 1000} = 432.42$, $P < 0.001$) and 2009 ($F_{20, 987} = 241$, $P < 0.001$) data indicated no significant difference between K1 and B1, nor between K4, K2, B5, B11, B7 and B2. There was also no significant difference between temperatures recorded at B10 and K6 (see Tables 5.6 and 5.7 and Figure 5.10)

Bed stability also varied within the upper braided section. Pfankuck score varied markedly from B7 with a highly unstable score of 47 to B13 with a relatively stable score of 17. The maximum difference is less than that between observed between the most (K8 =18) and least stable (K4=53) sites longitudinally, although it is certainly comparable. Bed material within different streams in the braided section also displays variability, with the D50 ranging from 0.22m in B10 to 0.0001m in B9, this compares to 0.10m at B7 in the main glacial channel.

Table 7.5 - Temperature and physical characteristics of sites from the upper braided section of Kårsavagge in 2008 (08) and 2009 (09), (not all sites were sampled in both years). Pfankuck index of bed stability (Pfank), bed gradient (Grad), D50. Relative roughness (Rel R), Substrate diversity (Sub div), Conductivity (Cond), pH, Total dissolved solids (TDS), resistivity (RES), Average temperature, (T min), Maximum temperature (T max), accumulated degree days (DD), and standard deviation of the temperature (Stdev). Temperature data for the corresponding time period from the main longitudinal sites (K1, K2, K4, K6, K8 and K9) is included for comparison.

Site	Pfank	D50 (mm)	Sub. Div.	Cond (µS)		pH		TDS (ppm)		Res (kohm)		Temperature (°C)									
												T Av		T Min		T Max		DD (days)		Stdev	
				08	*09*	*08*	*09*	*08*	*09*	*08*	*09*	*08*	*09*	*08*	*09*	*08*	*09*	*08*	*09*	*08*	*09*
B1	47	105.9	0.77	36.5	27.8	7.33	7.18	24.5	17.8	26.1	35.3	2.77	3.11	1.07	0.71	6.43	5.65	135.30	152.60	0.92	0.84
B2	32	46.0	0.65	25.2	11.9	7.23	7.47	16.7	8.0	40.5	78.2	4.34	5.04	1.33	0.51	9.84	9.34	213.60	246.50	1.46	1.56
B6	38	17.7	0.78	42.3	43.7	7.25	-	28.4	-	22.7	-	3.63	4.31	1.33	0.57	7.99	8.52	177.50	211.40	1.20	0.84
B7	48	50.7	0.80	43.4	26.7	7.38	7.63	29.1	17.3	22.3	36.4	4.25	4.60	1.99	1.92	10.01	8.11	208.00	225.70	1.24	1.13
B8	24	52.5	0.74	44.3	39.4	7.25	7.57	29.3	23.4	22.1	27.2	8.62	9.30	2.59	4.37	15.95	16.24	426.30	455.70	2.06	2.21
B9	21	0.1	0.00	48.7	55.9	6.84	-	32.2	-	19.9	-	8.44	8.64	2.59	5.03	12.53	11.68	416.90	423.20	1.36	1.14
B10	24	24.0	0.66	63.3	50.4	8.05	7.52	41.7	31.6	22.6	20.5	8.76	9.83	2.78	4.62	15.76	17.13	432.90	482.40	1.98	2.28
B12	37	32.0	0.71	-	29.2	-	7.33	-	18.0	-	35.2	-	8.68	-	2.84	-	15.38	-	424.70	-	2.51
B13	17	37.0	0.69	-	112.4	-	7.44	-	73.9	-	0.0	-	8.92	-	5.40	-	12.84	-	438.20	-	1.43
B14	22	62.0	0.63	-	53.21	-	7.5	-	35.4	-	18.1	-	8.64	-	5.03	-	11.68	-	423.2	-	1.43
K1												1.94	2.15	0.64	0.42	4.41	4.02	98.80	105.40	0.61	0.63
K2												4.67	4.99	2.28	1.86	9.77	9.04	233.30	244.70	1.38	1.30
K4												5.14	5.45	2.51	1.92	10.57	10.04	256.80	266.90	1.56	1.92
K6												9.66	10.16	7.52	7.52	13.75	15.47	483.00	497.00	1.08	1.57
K8												11.24	12.00	6.91	7.90	17.00	17.86	573.70	587.80	1.62	1.91
K9												11.03	12.33	4.63	7.35	17.13	18.01	562.50	604.10	1.86	1.98

Macroinvertebrate communities within the braided section show a similar structure as those observed longitudinally but different taxa dominated. In 2008 the most abundant taxa found from the individual samples was Accentrealla laponica (62%), followed by Chironomidae (18%), then Baetidae (9%) and Limiphilidae (4%). Data from the braids area in 2009 reflect the longitudinal macroinvertebrate samples more closely as they are dominated by Chironomidae (0.86%) with Limiphilidae (4%) and Agabinae (beetle larvae) (2%).

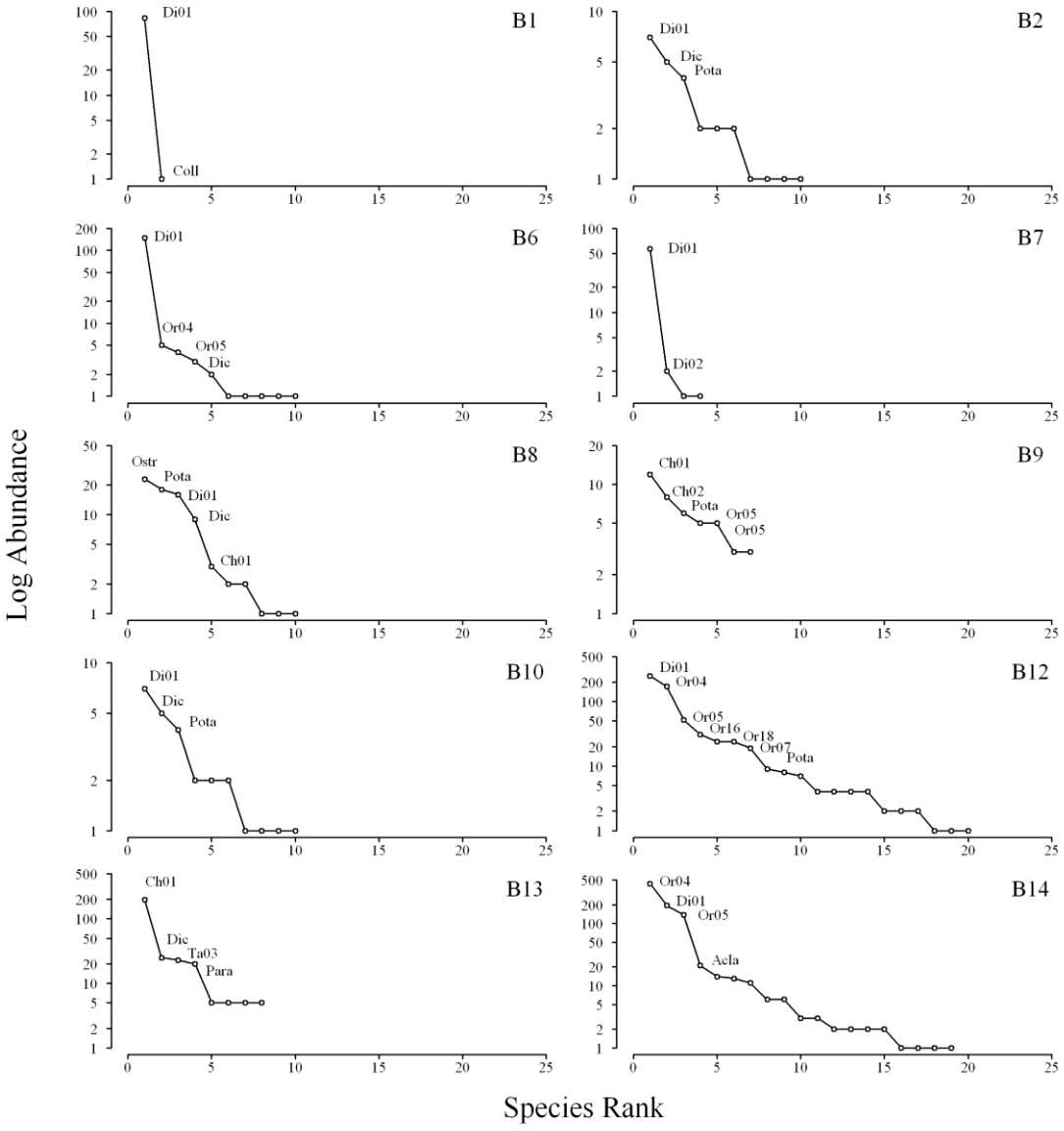

Figure 7.4 - Rank abundance plots for macroinvertebrate taxa encountered in samples taken in 2009 from sites within the upper braided section of Kårsavagge (B1, B2, B6, B7, B8, B9, B10, B12, B13 and B14). Data from each sampling event (n=2) have been pooled to produce one community for each site; Chironomidae have been identified down to genus. For species codes see appendix A.

Richness and diversity scores within the upper braided section displayed similar trends to those observed longitudinally (Table 7.1). These data suffered from a similar drawback to that observed in the longitudinal data in that Chironomidae were only taken past family in the 09 data but trends are still evident. The total number of taxa found within the braids in 2008 was 16 but increased to 24 in 2009, though it must be remembered that sampling was more extensive in 2009. Of the sites sampled in 2008 the highest Shannon diversity was found at B10 (1.68) which is comparable to diversity scores found in the longitudinal sites below the first lake. Other diversity scores cover the range observed longitudinally. A similar range of diversity scores is observed in the 2009.

Streams of the braided section can be grouped into those with high conductivity and dissolved ions (B10, B9, B8, B14, B12 B13) dominated by non glacial sources; those with some direct glacial influence showing lower conductivity and lower concentrations of dissolved ions (B1, B2, B6 and B7) When Chironomidae are taken further *diamesa spp.* were the most abundant group making up 29.7% of the total abundance, followed by *Cricotopus* (19.7%) and *Chironomini* (19.4%). The most abundant non-Chironomidae taxa were Limnephilidae which constitute 3.4% of total abundance.

The 2009 data highlights the shift in taxa dominance both spatially and temporally within the upper braided section of Kårsa valley. Samples from colder streams B1, B6 and B7 connected to the main glacial channel and B2 the North facing snowmelt stream were dominated by *Diamesa spp.* with low diversity and evenness scores (Table 7.1; Figure 7.4). *Diamesa spp.* are also the highest ranked taxa in terms of abundance in B12 and B10 and are prominent in B8, however these warmer, rhithral streams have much higher Shannon diversity and evenness.

Hill slope ground waters, B13 and B9 were dominated by *Microspectra spp*. Abundances were much greater in B13 which flowed into the main Kårsa than B9 which was not directly connected to the rest of the system. B14 a groundwater stream with a postulated source from upwelling glacier melt is intermediate between the snowmelt and glacial streams. The community is dominated by *Cricotopus spp* but *Diamesa spp* are also prominent.

Despite the distances much small distances between lateral sites compared to those longitudinally involved both average (0.69) and max (1.00) Beta diversity across the braids (lateral sites) in 2009 was higher than the equivalent scores (average = 0.69, max=0.82) longitudinally within the catchment.

7.4. iv) **Comparisons of longitudinal and lateral macroinvertebrate communities**

Ward clusters based on PAM analysis identified the optimum number of clusters to select to adequately describe the 2009 data is 9 (Figure 7.5). These groupings reflect longitudinal shifts and glacial influence. Group 1 included all samples from K1, the earliest sample from K2, B1, B2 and B7. Group 2 includes the remaining dates from K2, all K4 and samples from B12 and B14. Groups 1 and 2 were separated from the other groups by the first agglomeration which separated communities found in colder, less stable environments from those in warmer, more stable sites. Group 3 and Group 4 contain the remaining sites within the braids; group 3 is made of B10, B8 and the last B12 with B13 and B9, the two sites with the highest groundwater influence together in Group 4. Samples from the three lower sites are split into 5 groups. There was a clear

seasonal influence in the groupings as early season samples are separated from those taken later in the summer. Group 6 separated the middle season sample from K8 reflecting the spatial variability in macro invertebrate density. Groups 8 and 9 contain samples taken later in the season at sites K8 & K9 and K6 respectively. This clustering is graphically illustrated in the nMDS plot the bray Curtis distances (Figure 7.6). The seasonal trend is evident as samples below the lake move towards the center of the plot as the melt season progresses. There is a clear gradient from colder, more unstable sites on the left of the plot towards warmer more stable sites on the right.

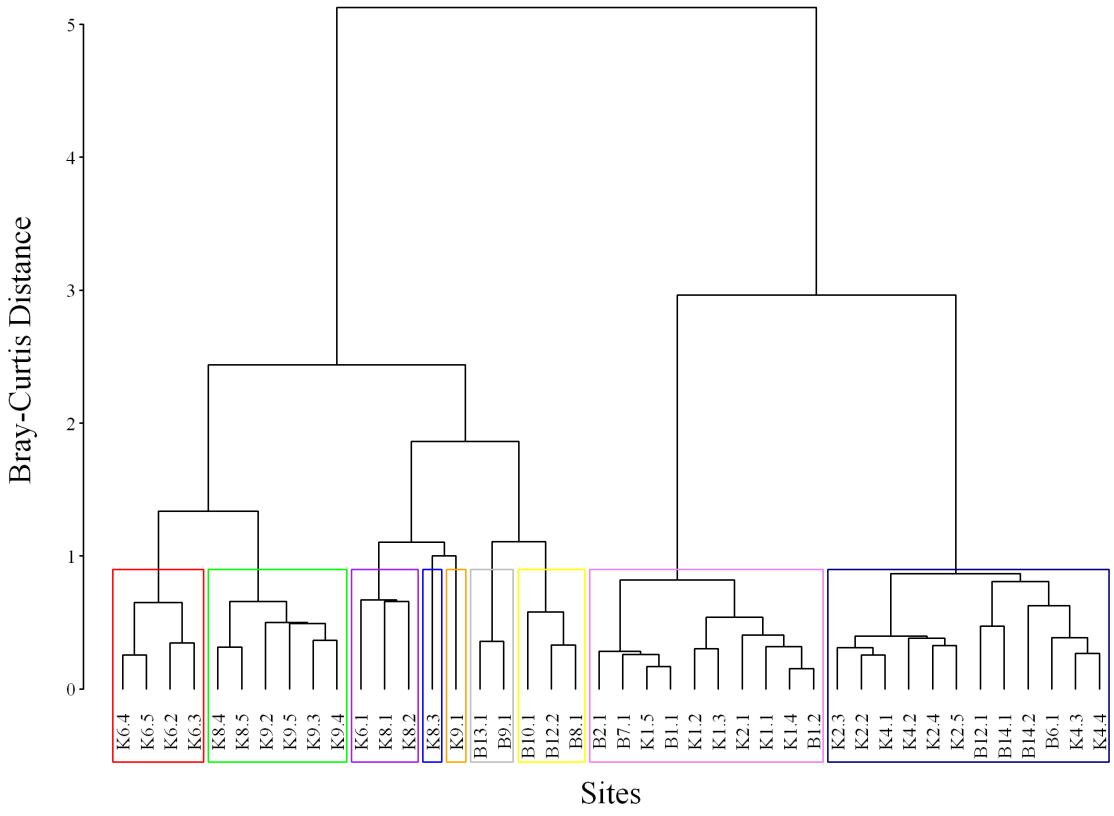

Figure 7.5 - Dendrogram grouping samples based on Bray Curtis distances between macroinvertebrate communities within Kårsavagge. Based on data collected in the 2009 and including samples from across the upper braided section (B1-B15) and along the main channel (K1-K9); Chironomidae have been identified down to genus. i.e. K1.1 = first sample date in 2009 at K1.

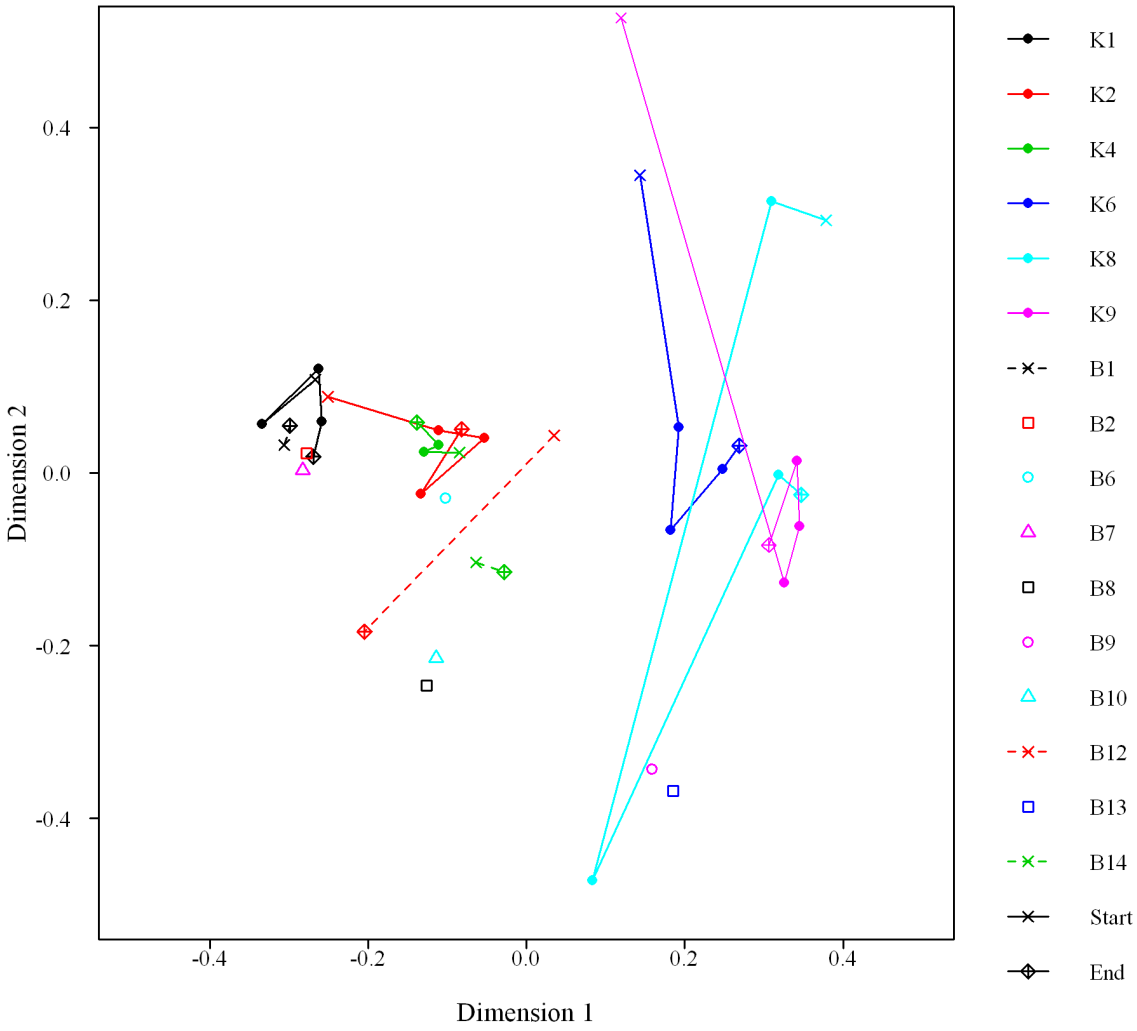

Figure 7.6 - NMDS plot of the trajectory taken by macroinvertebrate communities at each sample site within Kårsavagge in 2009 (B....= sites in the upper braided section, K...= the main longitudinal sites.). X signifies the earliest sampling point at any given site, ◈ signifies the final sampling event for any given site. Single shapes represent sites sampled once (pooled data from 5 replicates) during 2009.

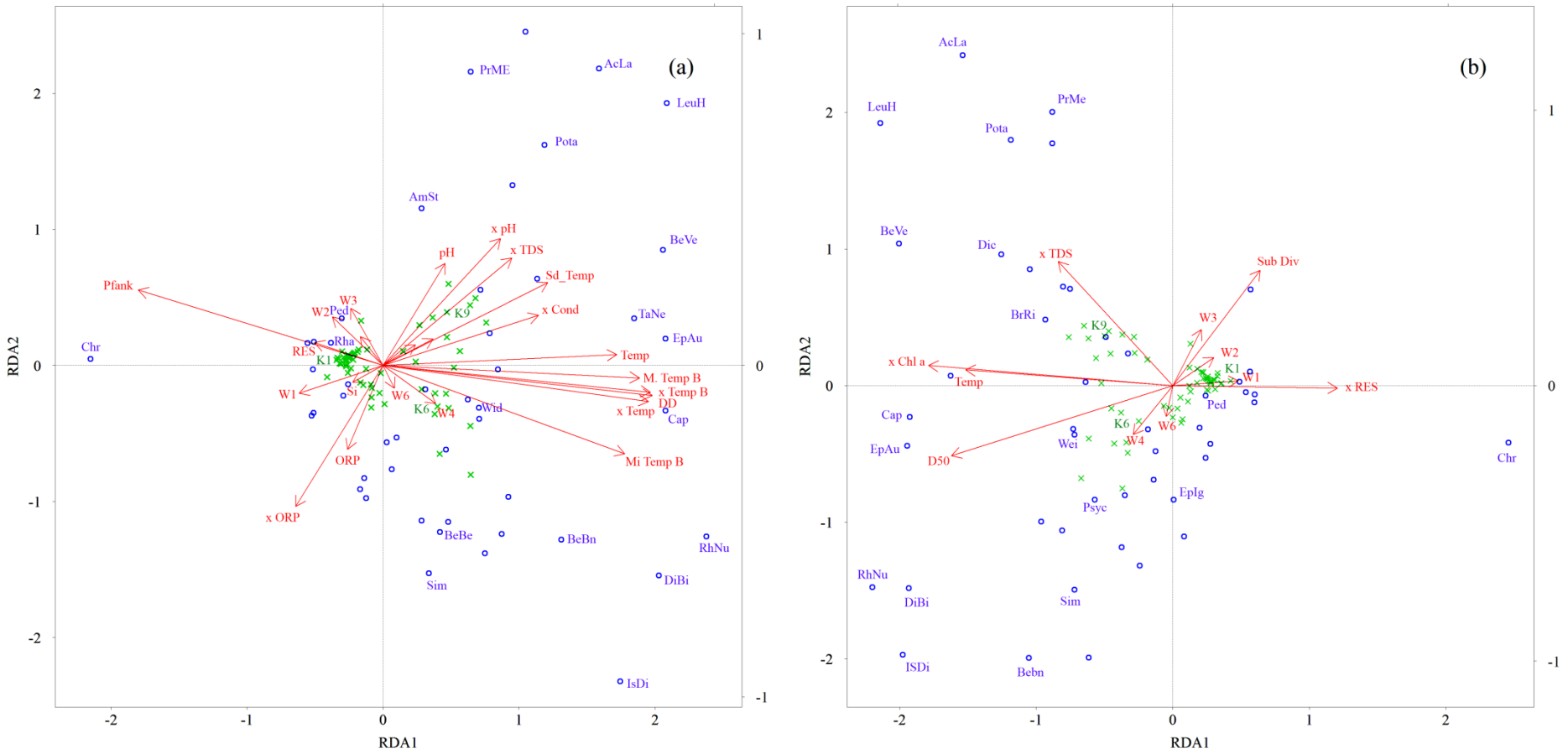

Figure 7.7- Redundancy Analysis of (lower resolution) macroinvertebrate data from 2008 and 2009 with environmental variables. (a) Full models including all non- redundant variables, (b) reduced model including D80, Chlorophyll a concentrations, total dissolved solids (TDS), substrate diversity (SD), resistivity (x Res) and sample week (W1 – W5). ○ = taxa, blue writing refers to invertebrate codes (see appendices for full names); **X** = Sample, green site codes are positioned in the region of the plots where samples from that site occur most often. Not all taxa are labelled for clarity

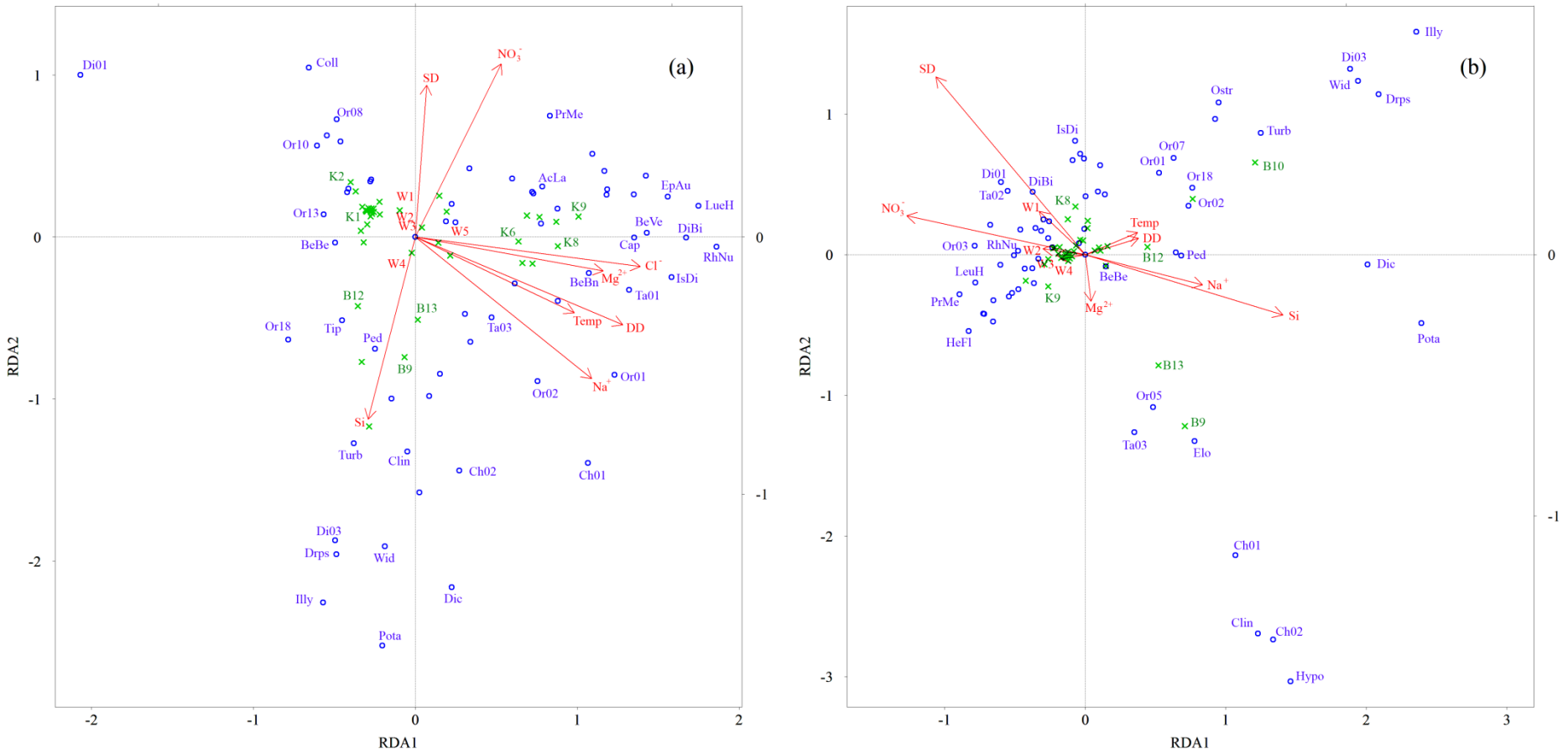

Figure 7.8 - Redundancy Analysis of 2009 macroinvertebrate data (high resolution) with environmental variables. (a) reduced model including substrate diversity (SD), accumulated degree days (DD), silica concentration (Si), Sodium concentration (Na^+), temperature at time of sampling (Temp), magnesium concentration (Mg^{2+}), nitrate concentration (No_3^-) week and chloride concentration (Cl^-). (b) reduced model with variation due to Cl^- partitioned out. See text for full explanation. ○ = taxa, blue writing refers to invertebrate codes (see appendices for full names); **X** = Sample, green site codes are positioned in the region of the plots where samples from that site occur most often. Not all taxa are labelled for clarity

Table 7.6 – Summary of the main physical, morphological and chemical habitats within stream reaches where invertebrates were sampled. For more details see chapters 3-6. **Water temp** – Average near bed temperature recorded across both field seasons; **Hydro-period** – average number of consecutive days per year with near bed temperature remaining > 0°C (when temperature < 0°C the assumption is that there is no flow); **Flows** – description of flow regime based on hydrographs or personal observation; **SSC** – description of suspended sediment regime; **Width** – width of bankfull channel; **Stability** – assessment of relative stability (Pfankuch bed index scores); **Substrate diversity** – assessment of substrate diversity (Simpsons index); **RR**- relative roughness score; **Slope** – assessment of channel gradient, where measurement taken value is given, otherwise relative assessment provided; **D50** - grain diameter (mm) at which 50% of the sediment sample is finer; **TDS** – Total dissolved solids, assessment of the concentration of dissolved substances in water samples; **WS** – water source that dominates flow, D- distributed flow, Q- quick-flow, G – groundwater; **Moss** – average % moss cover of benthic samples (K...) or estimate of % moss cover from observation (B...). *Information presented in italics made from personal observation / estimates rather than measurements.*

Site	Water temp (°C)	Hydro-period (Days)	Flow	SSC	Width (m)	Stability (Pfank)	Substrate diversity	RR	Slope (%)	D50 (mm)	TDS	Ws	Moss (%)
K1	Very Low (1.6)	Short (120)	Highly variable and responsive	Very high but highly variable	7.8	Very low (51)	Very High (0.82)	High (0.74)	Moderate (4.3)	70	Low	DQ	0
K2	Low (4.3)	Long, (~360)	Highly variable and responsive	High but highly variable	17.9	Stable (36)	Very High (0.82)	Very high (1.05)	Steep (9.1)	65	Low	DQ	0
K4	Low (4.7)	Short (157)	*Highly variable and responsive*	High but highly variable	8.05	Very low (53)	Very high (0.80)	Low (0.59)	Moderate (3.5)	52	Low	DQ	0
K6	Med (9.0)	Med (204)	*Variable but buffered*	Low	15.2	Very high (19)	High (0.75)	High (0.75)	Shallow (0.8)	98	Low	DQ G	24
K8	High (10.8)	Low (141)	Variable but lagged and attenuated	Low	18.6	Very high (18)	Very high (0.81)	Very high (1.12)	Shallow (0.6)	1.33	Low	DQ	24
K9	High (10.9)	Med (192)	*Variable but lagged and attenuated*	Low	16.1	High (21)	Very high (0.80)	High (0.88)	Shallow (0.4)	105	Low	DQ	25

Table 7.6 continued

B1	Low (2.94)	*Short (157)*	Highly variable and responsive	*Very high but highly variable*	6.3	Low (47)	High (0.77)	-	*Moderate*	105.9	Low	DQ	*0*
B2	Low (4.7)	*Short (157)*	*Low but Highly variable and responsive*	*Low*	3.4	Stable (32)	Moderate (0.65)	-	*Steep*	46.0	Very low	Q	*5*
B6	Low (4.0)	*Short (157)*	*Low*	*high and highly variable*	0.6	Moderate (38)	High (0.78)	-	*Moderate*	17.7	Low	DQ	*0*
B7	Low (4.4)	*Short (157)*	*Highly variable and responsive*	*Very high but highly variable*	7.4	Low (48)	Very high (0.80)	-	*Moderate*	50.7	Low	DQ	*0*
B8	Med (9.0)	*Short (157)*	*Stable*	*Low*	1.3	High (24)	High (0.74)	-	*Shallow*	52.5	Low	Q	*25*
B9	Med (8.5)	*?*	*Low and Very stable*	*Low*	0.5	High (21)	Very low (0.00)	-	*Shallow*	0.1	High	G	*0*
B10	Med (9.3)	*Short (157)*	*Low but variable and responsive*	*Low*	2.0	High (24)	Moderate (0.66)	-	*Shallow*	24.0	High	G	*10*
B12	Med (8.7)	*Short (157)*	Low but variable and responsive	*Low*	2.3	Moderate (37)	High (0.71)	-	*Shallow*	32.0	Low	Q	*10*
B13	Med (8.9)	*?*	*Low and Very stable*	*Low*	0.4	Very high (17)	Moderate (0.69)	-	*Shallow*	37.0	Very high	Q	*0*
B14	Med (8.6)	*Short (157)*	*Stable*	*Low*	1.7	High (22)	Moderate (0.63)	-	*Shallow*	62.0	High	DQ G	*5*

7.4. v) **RDA plots**

Both the full and reduced RDA plots of the main channel sites illustrate the dominant pattern within the data is the longitudinal transition from upstream sites to those downstream (Figure 7.7). The constrained variables in the full model account for 47.8% of the total variation and although some of the variables have been excluded due to collinearity the dominant patterns within the data are still clear. Pfankuch score, Resistivity, SO_4^{2-} and Si concentration position towards the left hand side of the plot, whereas higher temperature was plotted the right hand side. Chironomidae are positively associated with higher Pfankuch scores and negatively associated with temperature. Conversely *Capnia spp* and *B. risi* show strong positive association with higher temperatures and are negatively associated with Pfankuch index. Aside from these taxa the main pattern in the species data is the high degree of scatter on the warmer, more stable right hand side of the RDA which contrasts with the few taxa just left of center and the Chironomidae plotting to the far left that are tightly bound to RDA axis 1. The implication is that above a threshold score along RDA axis one, factors other than water temperature and stability become important.

Table 7.6 illustrates the habitat template at the main channel sites above the lakes is dominated in the short term by unpredictable disturbances caused by high flows and/or high levels of SCC; and in the longer term predictable but extreme freezing events. The potential for the high diversity substrate to give refuge is negated by its high instability and the RDA suggests that it is only the Chironomidae that have the required traits to persist under these conditions. Below the first lake variability in flow and SCC reduces, temperatures increase. Sites are still subject to extreme freezing events but the increased

stability increases the chance of flow and thermal refugia being present. At these lower sites larger, longer lived taxa are able to persist. Food chains lengthen and predators appear as temperature, stability and thus productivity increase (Figure 7.1a). The presence of attached moss increases habitat complexity still further allowing a wider range of niches to be exploited, hence the bloom in diversity below the lakes.

The reduced RDA for the longitudinal data illustrates this further (Figure 7.7b). Variables retained to describe the data are chlorophyll *a*, Temperature at time of sampling, TDS, substrate diversity, D50, average resistivity and sample week. This reduced model can relate 30% of the variation within the data to the constrained variables, and of this, 50% is explained by the first two RDA axes. In this reduced model the first axis is very closely associated to gradients in average chlorophyll *a*, water temperature and resistivity, all of which show a strong longitudinal pattern. The second axis is associated with sample week, with later samples pulling towards the bottom of the plot. Again it is clear that above a certain threshold on RDA 1 Chironomidae dominate and below this different taxa are encountered depending on the sampling occasion. The plot illustrates that certain taxa are associated, such as *Isoperla difformis*, *Diura bicaudata* and *Rhyiacophila nubila*, which are found later in the season at sites with higher temperatures and chlorophyll a.

The RDA of the 2009 data (Figure 7.8) including sampling dates and sites within the braids illustrates similar patterns to that observed longitudinally, however the increased resolution and added site variability highlight different aspects of the data. The reduced RDA (Figure 7.8a) explains 48% of the total variation with 40% of this locked within the first two RDA axes. *Diamesa spp* are separate from other taxa, including other Chironomidae in a region towards the top left of the RDA described by low temperatures

and low average concentrations of Cl^+, Na^+ and Mg^{2+}. Towards the opposite corner, taxa occurring at higher temperatures are found but are separated by their site associations. Those taxa, such as *Isoperla difformis* and *Diura bicuadata* only collected in the main channel were plotted above the temperature arrow.

Those taxa which also occur in warmer channels within the upper braids plot below the temperature arrow, pulled downwards by their association with higher silicate concentrations and low substrate diversity. These include *Potamophylax spp* and several Diptera (e.g. *Widemannia*, *Dicronata*) and Coleoptera (e.g. *Ilybus spp* and *Dryops spp*.) larvae. The distribution of samples within the plot reflects the NMDS trajectories.

Sites within the upper braided section (B1-B16) present a highly heterogeneous set of habitat templates on which the invertebrate communities are structured (Table 7.6). Some reflect the glacial signal and are very similar in morphology and disturbance regime to K1. Others such as B10 and B8 retain the annual no flow, freezing event, perhaps freezing earlier than the main channel because of their smaller size, but also present a much reduced disturbance regime in the short term. This allows the high bed complexity found in the channels to be utilized and in the warmer, more productive channels fed from the South facing slopes (B10, B8, B9, B12, B13) a more complex community can persist. But species that dominate here are not identical to the more stable sites downstream as the period of no flow and cold temperature is more extensive and extreme. Stability in the long term is also likely to be less than in the main channels downstream as D50 is smaller and flows during spring snowmelt are liable to exceed anything recorded during summer.

When different elements of macroinvertebrate variability were investigated the strongest correlation with the data was shown by average chloride concentration. By itself average chloride accounted for 3% of the total variation within the data, however in combination with other variables this jumped to 33%, greater than the 20% variation that was not associated with Cl^- (47% of variation is not accounted for by the RDA plot). Figure 7.8b plots the reduced RDA of the 2009 data with the variation associated with Cl^- partitioned out. This removes the majority of variation associated with the longitudinal profile and as such many taxa separated longitudinally are closely associated within this RDA (e.g. *Diamesa spp* and *Diura bicaudata*). The plot is now dominated by variability in Si, NO_3^- and substrate diversity. The majority of taxa from the main channel plot in the left hand side of this RDA with lower Si concentrations and higher substrate diversity. Taxa occurring within the braids plot out in the right hand side of the RDA. Those from high silicate, low substrate diversity sites such as B13 and B9 (e.g. *Micropsectra spp* and *Paratanytarsus spp*) are found in the bottom right, others predominantly found in higher temperature and higher substrate diversity sites such as B10 and B8 (e.g. *Ilybus spp* and *Dryops* spp) plot out towards the top right**.** This distinction reflects the differences in habitat template (Table 7.6). Those species plotting to the right are subject to the major annual cessation of flow and freezing event. They either are highly specialised with resistance and resilience traits (e.g. *Diamesa spp*.) or effective colonists (e.g. Trichoptera or *Tipula spp.*).

7.4. vi) **Functional feeding groups**

Functional feeding groups of macroinvertebrate showed a clear pattern both longitudinally and laterally (Figure 7.9). K1, K2 and K4 were dominated by scrapers (>95%). This reflects the overarching dominance of Diamesa and Orthocladiinae at these top sites. A few shredders were found at K2 and K4. Below the first lake the range of feeding guilds increased with deposit feeders (e.g. *Chironominae*), shredders (e.g. *L. hippopus* and *I. differmis*), filter feeders (e.g. Simulidae spp.) and predators (e.g. *D. bicaudata* and *R. nubila*) all making contributions to total abundance. Despite this, the scraper guild remained dominant contributing over 70% of individuals, mostly Orthocladiinae and some B. bundyae. Further downstream, at K8, the high numbers of Simuliidae increase the proportion of filter feeders (39%) and this guild dominates, though relatively high contributions are made from shredders (20%), scrapers (27%) and predators (12%). Relatively high numbers of A. lapponica and Orthcladiinae account for the dominance (59%) of scrapers at K9, with shredders (30%) and predators (5%) also prominent.

Within the braided section those communities along the main channel reflect the guilds found at K1 and K2. B1 at the start of the braids contains almost exclusively (99%) scrapers dominated by *Diamesa spp*. Other main channel sites B6 (95%) and B7 (95%) were similarly weighted in favour of scrapers. Snowmelt streams B12 and B2 were also dominated by scrapers but had a greater influence from other guilds, particularly shredders (e.g. *Potamophylax* spp). Channels with low values of D50 and groundwater dominated sources such as B13 and B9 had a high percentage (74% and 24% respectively) of deposit feeders. Piercers make up a considerably higher proportion of

total abundance within the braids than longitudinally due to the number of coleopteran larvae encountered. This is most evident in B10 where piercers made up 18% of the total abundance.

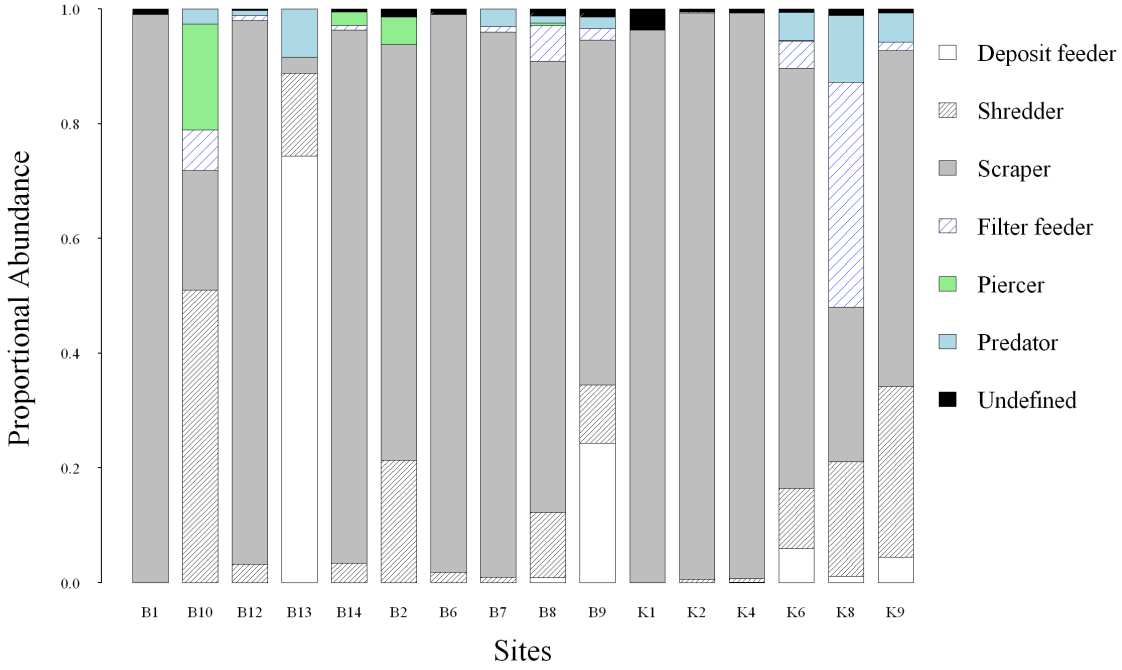

Figure 7.9 – Proportion of macroinvertebrates from different functional feeding groups found across all sites within Kårsavagge sampled in 2009 (B... = sites within the upper braided section, K...= sites along the main channel). Feeding groups defined using protocol outlined by Tachet *et al.*, (2000) and Bis and Usseglio-Polatera (2004).

7.5 Discussion

7.5. i) **Longitudinal physicochemical habitat variables**

Kårsavagge displays strong longitudinal gradients in physicochemical habitat variables. Temperatures increased steadily along the main Kårsavagge channel, due to a combination of warmer water inputs, atmospheric forcing and the warming from the top lake (Bajimus Gorsájvri). This lake plays a major role in the longitudinal transition of the Kårsa. Sites along the main channel above the lake display a strong glacial signal with high suspended sediment loads, high Pfankuch scores (except at K2), low chlorophyll a, low average water temperature and strong diurnal variability. K6, just below the lake outflow is characterized by high stability, high chlorophyll a, very low suspended sediments and a relatively warm, stable thermal regime (Figure 7.1, Tables 7.2 and 7.6). This attenuated physical regime is maintained at subsequent sites (K8 and K9), although solar forcing and rhithral inputs do raise thermal variability slightly. The capacity for lakes to act as 'discontinuities' or 'habitat modifiers' within the longitudinal regime has been noted by several authors (Kling *et al.*, 2000; Brittain and Milner, 2001; Hieber *et al.*, 2002; Uehlinger *et al.*, 2003; Arp *et al.*, 2006; 2007; Robinson and Matthaei, 2007;) but the extent to which conditions in the outflow are modified with respect to the inflow is dependent on initial water source, shading, lake morphology and position within the river profile (Hieber *et al.*, 2002; 2005; Arp *et al.*, 2007; Robinson and Matthaei, 2007).

Hieber *et al.* (2002) found that although there were significant impacts of lakes on thermal and chemical regime, the key aspect with regards to bed stability was the stream type of the inflow, with Kryal inflows leading to outflows retaining the kryal stability

scores; stability in outlet streams from lakes with rhithral source waters was greater than that of the inflow. In contrast, Uehlinger *et al.* (2003) found that a proglacial lake outlet had reduced bed movement with respect to the proglacial stream.

The strong ameliorating effect of Bajimus Gorsájvri on the glacial signal in this study is probably related to its size and position within the system. Hieber *et al.* (2002) looked at high gradient (>2%) outlets from small lakes (surface area < 0.27 km2), at high altitude (>1900m), in an Alpine environment. In comparison Bajimus Gorsájvri is relatively large (0.95 km2) and deep (max depth ~32m), at an altitude of only 700m with a relatively shallow bed gradient at its outlet (~0.08%). The lake inlet is also 3.3km from the glacial snout and several rhithral tributaries enter in between the two. The low gradient reduces sheer stress (Gordon *et al.*, 2004b) meaning discharges need to be higher to result in bed movement, the large volume will buffer diurnal and storm related high flows (Arp *et al.*, 2006) and the mixing of water sources dilutes the pure glacial signal of the inflow (Brown *et al.*, 2003). This combination of site specific factors results in a lake with much greater potential for attenuation than those Hieber *et al.* (2002) investigated, sporting an outlet stream with a much more benign regime than that of its inlet.

7.5. ii) **Lateral physicochemical habitat variables**

The extent of lateral habitat variability within glacial floodplains has only recently been investigated (Arscott *et al.*, 2001; Uehlinger *et al.*, 2003) but this lateral component has been shown to contribute significantly to overall habitat heterogeneity. This is particularly true of thermal variability, where observed water temperature ranges with a

floodplain have been seen to exceed those longitudinally (Arscott *et al.*, 2001; Uehlinger *et al.*, 2003).

High habitat heterogeneity was observed in Kårsavagge despite limiting lateral investigations to a small region in the upper catchment. Within this section physicochemical variability between different channels laterally (<0.3km) was equivalent to that observed over the entire longitudinal profile of the main channel (18.3km).

7.5. iii) **Macroinvertebrate community**

The theory of the physico-chemical habitat templet has a long history in stream ecology (Minshall, 1988; Poff and Ward, 1990; Poff *et al.*, 1996; Huryn, 2005; Milner *et al.*, 2006; Füreder, 2007; Sheldon, 2009; Uehlinger *et al.*, 2010) and is often cited as the strongest filter determining the potential species pool for any given environment (Walther *et al.*, 2002). An understanding of the local and regional habitat templet of Kårsavagge is helpful in understanding both the current distribution of taxa and the potential response of communities to environmental change.

Like most river networks, Kårsavagge can be seen as a nested hierarchy of systems (Frissell *et al.*, 1986; Poff and Ward, 1990; Smith *et al.*, 2001; Arscott *et al.*, 2005), with changes in one cascading down to influence the structure and function of those subordinate to it (Hildrew and Townsend, 1994; Hieber *et al.*, 2005). Standing on the watershed looking down, the whole catchment may be broken down to sub-catchments; delineated by discontinuities such as the lakes or changes in bedrock. These can be

further divided: a segment> reach> pool-riffle> and lastly a microhabitat (Frissell *et al.*, 1986; Poff and Ward, 1990). If we were then rise in a hot air balloon it would become clear that Kårsavagge itself is nested within larger bio-geographic and regional climatic systems. Each system filters taxa, with extra filters presented by subsequent levels through which taxa must pass if they are to persist, right down to specific micro-habitat envelopes or patches (Huryn, 2005; Heino *et al.*, 2007). It must be noted that persistence at one level does not mean a taxa is ubiquitous within all its nested sublevels, simply that at any given time a population is present in one or more microhabitats (Begon *et al.*, 2002).

In reality over geological time stable ecosystems come about through the concomitant evolution of environment and taxa from some virgin system and original gene pool to what is currently observed (with the addition of successful colonists). The concept of habitat filters is none the less a good way to identify traits already present within a community and therefore available to respond to disturbance (Poff and Ward, 1990).

Currently, the dominant filter operating at the catchment scale in Kårsavagge and all arctic habitats is the extreme seasonality of the climate (Danks *et al.*, 1994; Olsson *et al.*, 2003; Danks, 2004; Huryn, 2005; Füreder, 2007; Milner *et al.*, 2009). All macroinvertebrates and indeed all organisms persisting have traits equipping them to cope when flows cease and temperatures fall (Strathdee and Bale, 1998; Danks, 2004; 2007; Winterbourn *et al.*, 2008; Lencioni *et al.*, 2009). In terms of the habitat template, the arctic winter would be classed as a high magnitude, predictable, long term pulse event (Townsend and Hildrew, 1994; Lake, 2000). This is only from the perspective of those species for which the summer provides preferential conditions; given the hydro-period for

some sites (e.g. K1) it could be argued that the melt season is the disturbance event (see Uehlinger *et al.*, 2010). Townsend and Hildrew (1994) suggest that the more predictable a disturbance the lower its impact, as taxa evolve to adaptively avoid or mitigate impacts. Hence even taxa that are not freeze tolerant can persist through behavioural adaptation such as utilizing refugia or an evolved resistant life stage (i.e. *Aeides nigripes* eggs) (Danks *et al.*, 1994; Danks, 2007). The former is only needed if generation time is long enough to encompass the winter, which for many multi- or univoltine species (*Diamesa incallida*) (Walker) (Nolte and Hoffmann, 1992). Semi-voltinism is common in arctic taxa due to the low productivity and cool temperatures (Strathdee and Bale, 1998; Danks, 2004; Finn and Poff, 2005) species that are not freeze tolerant will only fit through a habitat filter which provides appropriate refugia. If no winter refugia are present then there will either be no individuals or an ephemeral sink population, maintained through oviposition by adults dispersing from permanent populations elsewhere.

In some Alpine streams, with significant groundwater input, benthic conditions ameliorate as winter sets in (Battin *et al.*, 2004; Uehlinger *et al.*, 2010). The cessation of glacial melt reduces SSC and inputs of near freezing water. This provides a window of high productivity in flows dominated by groundwater and in these systems resting stages may be required to mitigate the impact of spring and summer flows. In Kårsavagge, and other arctic systems windows of productivity are limited by winter insolation and the lack of groundwater input (ACIA, 2004).

As there are hierarchies of spatial scales, so there are hierarchies of temporal scales. The occurrence of diel flow ‘events’ in arctic and alpine streams is well documented (e.g. (Ward, 1994; Füreder *et al.*, 2001; Arscott *et al.*, 2003; Brown *et al.*, 2003; Hieber *et al.*,

2003; Malard *et al.*, 2003; 2006; Silveri *et al.*, 2009). Diel flow events are both low in magnitude and highly predictable so have limited impact on the post event community. Rainfall events in contrast present an unpredictable disturbance. The impact of each rainfall event is dependent on its magnitude and duration, the antecedent conditions and catchment morphology (Caissie, 2006; Brown and Hannah, 2007; Cadbury *et al.*, 2008). If flows rise faster than during the diel increase or exceed normal levels (as observed at K1, K2, B1 and B12 see Figure 5.2 and 5.3) then impact may be high. In this instance habitats that are insufficiently stable or varied to provide refugia against large scale extreme impact events (such as spring melt) may y*et al*low communities to mitigate more frequent but unpredictable medium magnitude flows. This may be one factor accounting for the more extensive and diverse macroinvertebrate communities found in more stable channels within the upper braided section when compared to the highly unstable main channel.

The difference between communities sampled in the upper section of Kårsavagge is also dependant on habitat filters presented by the dominant water source. The main glacial channel is subject to high SSC, the most extreme diel flows, and constant low temperatures. These filter off all taxa which would be damaged by the scouring sediment concentrations, cold temperatures or require a high algal resource. In contrast, some channels in the upper braided section attain temperatures above 10°C due to their size and aspect. These more stable, warmer channels support patches of moss (increasing benthic habitat complexity (Bowden *et al.*, 1994; Suren, 1991) and algal production is liable to be relatively high. The filters presented by these channels result in a wider variety of traits, including generalists when compared to the specialists of the glacial stem.

Referring back to Poff and Ward (1990) the patchy habitat template of Kårsavagge has produced a variety of traits. Communities along the main glacial stem above the lakes (K1, K4 and K3) are dominated by cold stenothermal taxa resistant to disturbance. Those in the upper braided section (B1-B16) are dominated by more generalist, eurythermal taxa with short generation times, resting stages or effective dispersive adult phases. Traits below the first lake tend towards behavioural freeze avoidance, eurythermal tolerance, and specialism's relating to resource acquisition such as filter feeding/ predation.

Even within the harsh physical and climatic envelope presented by Arctic water courses ecoclines exist and different communities dominate at different points along these gradients. The most obvious habitat gradients within glacial stream systems occur longitudinally (as described above for Kårsavagge) where 'harshness' decreases with increasing distance from the glacial source. Milner *et al.*, (2001a) plot community development along gradients of temperature and stability, this deterministic model predicts that non dipteran and oligochaeta species will colonize the main channel when maximum temperatures exceed 4°C.

T^{max} above 4°C was recorded at all of the main channel sites in Kårsa however members of the >4°C community predicted by Milner *et al.* (2001a) including Perlidadae, Taeniopterygidae, Baetidae, Simuliidae and Empididae were only common in samples downstream of the top lake. Selected taxa from this community were infrequently found at K2 (in 2008 one individual of *I.diffomis*, two individuals of *A.sulicollis* and occasional *B. vernus* and *A.lapponica*; in 2009 one individual of *B. vernus*) but *Diamesa* remained overwhelmingly dominant in all samples (see Figure 7.5). This is essentially a hypokryl community as described by Ward (1994a) and its extension to K4, over 2km from the

glacial snout despite a T max well above that associated with the kryal biotope highlights the importance of dominant water source and bed stability in mediating community composition.

Snook and Milner (2001) found that a hypokryal community extended 900m away from the Tiallon glacier where T^{max} > 13°C and a similar observation was made by Gíaslason *et al.* (2000) who recorded *Diamesa spp*. dominating up to a T^{max} 18°C. Snook and Milner (2001) suggest that the influence of T^{max} in these systems is superseded by the high instability of the main glacial channel. They also suggest that the high glacial influence and potential drying up of these streams may limit colonisation by Ephemeroptera, Plecoptera and Trichoptera (EPT). Although it is unlikely that the main channel in Kårsavagge above the lake will run dry, overwinter thermal investigations suggest that it freezes to the bed for a period during the winter.

SSC, slope and the strength of the diurnal flow regime are much greater in the upper catchment than at the lower sites and Pfankuch scores indicate bed stability is low. It is probably a combination of these factors that prevent more euryzonal species establishing viable populations. Flory and Milner (1999) illustrated that *D. Alpines*/ *lupus*, mainly found within kyral streams in Wolf Point Creek is capable of maintaining populations in rhithral conditions so long as competitors are excluded. The introduction of *P. Particus* into experimental channels resulted a reduction density of *D.alpines*/ *lupus*. This fugitive nature may well be a common trait in *Diamesa spp* that require a highly disturbed environment rather than low temperatures to maintain dominance during the summer months. Several studies on alpine glacial streams have shown that the reduction of glacial influence during winter is associated with a shift in the biotic community from kryal to a

more rhitheral assemblage (Ward *et al.*, 1999; Klein and Tockner, 2000; Burgherr and Ward, 2001; Robinson *et al.*, 2001). These investigations were all carried out in lower latitudes, where groundwater inputs maintain flows and seasonality of received solar radiation is not as extreme as in the Arctic.

Overwinter water temperature records in Kårsavagge suggest that at least some sections of the upper stream freeze to the bed and even if certain patches do not, the reduction in solar input will restrict primary productivity (ACIA, 2004). Some macroinvertebrate families such as Diamesinae and Empidae have been shown to display degrees of freeze tolerance (Olsson, 1981; Danks, 2007), but the majority of cold adapted species practice freeze avoidance (Irons *et al.*, 1993; Lencioni, 2004) and have very low survival rates where water freezes to the bed or they come in contact with ice (Frisbie and Lee, 1997). Although windows of opportunity as described by Uehlinger *et al.* (2002) may represent periods when the kryal biotope can increase productivity they will have limited impact of biodiversity in Arctic systems such as Kårsavagge due to a lack of winter refugia for freeze intolerant taxa.

The bloom in diversity that occurs at K6 from acquisition of: Perlodidae, Taeniopterygidea, Simuliidae, Rhyacophilidae, Empididae, Ephemerellidae suggests that the lake plays a significant role in structuring the macroinvertebrate community within Kårsavagge. Along with the acquisition of previously unrecorded families, the 2009 data reveal a turnover in the Chironomidae community. *Diamesa spp*. dominance above the lake shifts to Orthocladiinae dominance below it and the subfamilies Chironominae and Tanypodinae appear. This expansion in species richness is illustrated by the change in shape of rank abundance curves longitudinally (Figure 7.3). Although model fitting

showed that all sites conformed to the either Zipf (K1, K2 and K3) or Zipf-Mandelbrot (K6 and K9) models, the change in shape suggests a shift towards a dominance-decay model as one moves down stream. Indeed the difference between the Zipf and Zipf-Mandelbrot models is caused but an extra parameter within the Zipf-Mandelbrot model relating to niche diversity, implying community structure does indeed become more complex below the lake competition for space/ resources becomes important (Wilson, 1991; Begon *et al.*, 2002).

This shift is facilitated by the presence of the lake which as noted earlier, reduces SSC and Pfankuch scores (Table 7.5). There is also a significant rise in primary productivity, probably related to this increase in bed stability and water clarity. The RDA and NMDS plots (Figure 7.7, 7.8 and 7.9) emphasise the importance of the lake in terms of community structure within Kårsavagge. Chironomidae are strongly associated with PBI and other species spread around the plot in a conical shape with Chironomidae at its apex. Once PBI drops below a certain threshold the habitat moves away from the deterministic bottle neck and a combination of increased habitat heterogeneity and stochastic interactions result in a greater spread of site samples within the RDA and NMDS plotting space. The NMDS also highlights some seasonal trends in the data. Along with the gradual trajectory form left to right within the plotting region as sample week progresses, the first sample date in 2009 for K6 and K9 are distinct from subsequent ones. This is due to the much reduced richness and benthic invertebrate density of the early season samples from this year. Arp *et al.* (2006) found that a lake in the Sawtooth Mountains, Idaho, had limited impact on peak flows during spring snowmelt but played a significant role attenuating peak flows throughout the rest of the melt season. They also illustrate the

influence of a lake is greatly reduced by 4km downstream. A similar response by the first lake in Kårsa would result in the observed taxa distributions. The initial unattenuated discharges of spring snowmelt result in high sheer stress and low stability that is either not readily accounted for by PTI (Jacobsen *et al.*, 2010) or occurred before the study period with residual impacts. By the second sampling occasion flows reduced and other taxa appear to make use of the relatively benign habitat. The lack of this start of season signal in 2008 may relate to differences in timing of melt initiation. Positive temperatures were recorded 22 days earlier at K9 in 2009 than 2008 however the thaw at the top sites was only 4 days apart. Invertebrates are known to use various cues to exit diapause, one of which is temperature (Gullan and Cranston, 2010). The earlier, high temperatures at the lower sites may have resulted in some invertebrates breaking diapause before the onset of peak flows and as a result, being prone to increased incidence of catastrophic drift.

The invertebrate community sampled at K8 has much reduced density in the majority of samples with respect to K6 and K9. The exception to this is the first sample in 2008 when the benthic community is overwhelmingly dominated by Simuliidae. The low average densities at K8 may reflect site specific constraints, in both years unidentified deposits coated much of the rock and moss surfaces and this may have had direct negative impacts on the Macroinvertebrate community. The Simuliidae peak may simply reflect an extreme example of the highly stochastic nature of small populations in the Arctic and the patchy distribution of stream invertebrates (e.g. Smock *et al.*, 1992; Brunke *et al.*, 2003) or the lack of a 2009 peak may be a result of the timing of spring melt as alluded to earlier.

Alternatively the relatively low numbers at K8 could reflect the 'real' stream community at that altitude. In this instance K6 could be described as an outlet community, a special case not concordant with the rest of the stream and K9 a much lower altitude site could be said to be in a non comparable zone.

7.5. iv) **Comparison of longitudinal and lateral sites**

Robinson and Matthaei (2007) showed that a high level of habitat heterogeneity exists within the glacial river floodplain associated with the Val Roseg glacier. Local habitat diversity results in high local beta diversity scores as particular species assemblages are associated with specific environmental conditions. This has been illustrated in several studies of glacial basins where stream types, often associated with dominant water source (Brown *et al.*, 2003) are associated with a specific community assemblage (Ward, 1994; Brunke *et al.*, 2003; Arscott *et al.*, 2005; Brown *et al.*, 2006d; Gray and Harding, 2009). The braided system at the top of Kårsavagge is a matrix of stream types displaying variability in flow regime, SSC, moss cover, PTI, sediment diversity and D50 (See chapter 3 for description, chapter 5 for analysis of thermal habitats, chapter 6 for variation in water chemistry and Table 7.5). PAM analysis on the combined longitudinal and lateral data sets identified 9 different clades. The main split in the data separated out longitudinal sites above the first lake, from those below; however lateral site samples from within the braided section bridged this gap. Invertebrate communities observed in some of the lateral channels were more similar to the main channel 14km downstream than they were to channels a few meters away. Indeed, average and maximum recorded values of Beta diversity across this region of the floodplain were equivalent to those

observed along the entire longitudinal section of Kårsa that was sampled. These differences may be intuitive given the range of physicochemical conditions within the upper braided section, however the small distances over which these shifts biotic community occur mark out braided regions in the upper parts of glaciated systems as 'hotspots' of invertebrate diversity.

The strongest gradient in the full model appears to be that moving from low stability in the bottom right to high temperature in the top left. This supports the dominant gradients as proposed by Milner *et al.* (2001a) and suggests that they are relevant for all for all Arctic and Alpine lotic streams, not just along main glacial channels. However, where these the only defining gradients it would be expected that invertebrate communities sampled in relatively warm, stable channels in the upper catchment would simply reflect similar patches of the main channel which have equivalent temperature and stability. However the data suggests this is not the case; there is a split between those stable, warm sites above the lake such as B8, B9, B10 and B13 and main channel sites below it.

Those taxa present in the total Kårsavagge species pool, but not encountered in the upper braids are mostly from the orders Plectoptera, Trichoptera and Ephemeroptera. Despite the numbers of Beatidae and the occasional Limniphilidae encountered within some channels, there was a large portion of the EPT species pool excluded. This is unexpected as despite the frequently noted dominance of *Diamesa spp* in main channel communities in glacierized regions; rhithral and krenal streams frequently support a varied range of EPT taxa (Hieber *et al.*, 2005; Brown *et al.*, 2006d). Snook and Milner (2001) suggested that dewatering of a channel, either through freezing or drying out prevented the formation of more complex communities. It has been widely noted that many

macroinvertebrates in the Arctic require more than one year to reach maturity (Ulfstran 1968; Brittain, 1990; Danks, 2007) but few are truly freeze tolerant (but see Walters *et al.*, 2009). In sites with no reliable overwinter thermal refugia, populations are likely to be maintained by summer migrants, with numbers highly stochastic and local extinction likely.

The limited depth of the channels in the upper braids, and the fact that waters are sourced from glacial melt, snowmelt or shallow ground water (its self reliant on melt water) suggests that they will freeze/ run dry at some point during the winter. Endopterygota (e.g. Diptera, Coleoptera and Trichoptera) tend to be more freeze tolerant than Exopterygota (e.g. Ephemeroptera and Plecoptera) which may explain their relative dominance at these sites (Vernon and Vannier, 2002). The only EPT family frequently recorded in the braided channels was *Beatis spp*. Several northern *Baetis spp* such as *B. Vernus, B. Alpinus* and *B. Bundiyae* have been reported as having summer univoltine life histories, overwintering as freeze tolerant eggs (Clifford, 1982; Giberson *et al.*, 2007). This life history trait, along with rapid dispersal allows them to take advantage of ephemeral, Arctic and Alpine streams such as those in the upper braids. The expansion of local richness recorded below the lake K6 may relate to the size of the channel and increased hyporeic depth providing a more reliable winter refugia. The impact of the top lake as a thermal refugia may also be significant. Although many of the EPT taxa are associated with lotic conditions, at high latitudes where colder more oxygenated water is more widespread, niche breadth expands (Ulfstran, 1968) and various Plecoptera, including *Diura bicaudata* and *Capnia atra* have been recorded in lentic habitats in

(Ulfstran, 1968; Brittain, 1983). Semivoltine taxa will expand from these refugia following spring melt to the more productive lotic regions of the system.

7.5. v) **Functional feeding guilds**

Analysis of the feeding guilds illustrates that there is a strong increase in the percentage abundance of shredders longitudinally. Reduction in altitude and greater bank stability are associated with the development of a more complex riparian vegetation (Gurnell *et al.*, 2000) and as a result as an increased amount of allochthonous inputs (Vannote *et al.*, 1980). Although the amount of CPOM was not measured within Kårsavagge it was clear that volumes of organic matter increased downstream as bank side vegetation developed. There was also an increase in the percentage of shredders laterally within the braided section, following the gradient of reducing harshness. The trait index used to define dominant taxa traits was that produced by the star group (Bis and Usseglio-Polatera, 2004). Many of the taxa included in the shredder guild have also been recorded as scrapers (Bis and Usseglio-Polatera, 2004) and based on the proportions within the braided section and the limited allochthonous input in this region I would suggest that the pattern observed longitudinally should take this into account. The increase in bed stability and autochthonous production downstream (supplemented by the addition of allochthonous material) enables a broader range of taxa to colonize. These epizonal, omnivorous taxa, less specialized than the stenothermal scrapers that dominate the upper catchment are none the less able to compete for all the available resources when conditions ameliorate. It is this, rather than simply an increase in exogenous material that drives community expansion both longitudinally and in the braids. As different taxa

dominate the scraper guild upstream and downstream of the lake further investigation would be required to confirm this hypothesis.

Springs streams often highly specialised communities (Klein and Tockner, 2000; Cantonati *et al.*, 2006). The main spring stream in Kårsavagge also has a strong deposit feeder guild dominated by Chironomidae. Stable flows and warm temperatures, in combination with water a chemistry that often yields iron precipitates can lead to high bacterial production which supports a relatively high Chironomidae density (Cantonati *et al.*, 2006).

The filter feeder guild was dominated by Simuliidae and concentrated at K8, with some individuals in K6. This distribution may relate to the impact of lakes in series. In contrast to temperate zone lake outlet communities which are dominated by filter feeders making use of washout of pelagic particulate organic matter (Richardson and Mackay, 1991) oligotrophic cold lakes act as sinks rather than sources of organic material (Hieber *et al.*, 2003). However distinct lake outlet communities have been observed in some high latitude systems (Ulfstran, 1968). Given the low percentage of filter feeders encountered at K6 it can be presumed that the impact of POM export is much lower than the impact that the reduction in harshness has on primary productivity. The second lake in the system is much shallower than the first, and is fed by a more benign input channel. Hieber *et al.* (2005) found that lakes with rhithral inputs had significant impact on the output community and Arp *et al.* (2007) showed that lake impacts could be transmitted at least 2km downstream. Pelagic productivity in the second lake may well be relatively high and export POM downstream as far as K8 explaining this increase in filter feeders.

7.6 Conclusion

The aim of this chapter was to relate the distribution and diversity of macroinvertebrate communities to physical habitat variables and provide information regarding potential shifts due to climate change. The key outcomes of the chapter are:

1) Species assemblages are dominated by Chironomidae, especially upstream of the first lake. The key habitat variable structuring the community longitudinally is the first lake. This mediates the glacial signal ameliorating conditions downstream enabling a more complex and diverse macro-invertebrate community to establish.

2) Lateral diversity plays a major role in overall macroinvertebrate diversity of Kårsavagge. The range of stream physicochemical habitat conditions brought about by shifting water source dominance in the upper braided section produced shifts in the macroinvertebrate community over a few metres as that seen along the entire 28km length of the main channel.

3) With a view to predicted climate change, species assemblages within Kårsavagge are structured according to an Arctic habitat template dominated by water source and winter temperature regime. If the glacial signal reduces due to climate change the interaction of these water sources will change causing a concomitant alteration of benthic conditions in some (potentially all) stream types. This will likely produce a migration of more euryzonal species towards the headwaters. However it appears that a constraint on the communities of shallow headwater streams in Kårsavagge is drying/ freezing, so until

sufficient winter refugia appear or winters warm up, more the more euryzonal species may have very stochastic populations in the headwaters.

Chapter 8 - Arctic Charr of Upper Kårsavagge

8.1 Introduction

The Arctic charr (*Salvelinus alpinus*, Linnaeus, 1758) is a circumpolar species displaying the most northerly distribution of any freshwater fish (Hammer, 1985).Arctic charr are often described as epibenthic, however a high degree of trophic, morphological and behavioural plasticity enables them to exploit a range of different ecological niches (e.g. Fraser *et al.*, 1998; Gulseth and Nilssen, 2001; Gallagher and Dick, 2010). Within landlocked lakes resource polymorphism has led to four ecologically distinct and in some cases reproductively isolated morphs (Malmquist *et al.*, 1992; Jonsson and Jonsson, 2001). Research into these morphs tends to focus on the sympatric populations of the smaller, benthic feeding morph, often referred to as dwarf charr and the larger piscivorous morph, although larger benthic and planktivorous morphs have also been observed (Malmquist, 1992; Jonsson and Jonsson, 2001; Arbour *et al.*, 2011).

Figure 8.1 – Example of immature Arctic charr from Kårsavagge.

Arctic charr undergo ontogenetic shifts in diet and habitat (Klemetsen *et al.*, 2003a; Eloranta *et al.*, 2010). Habitat use is a trade-off between resource acquisition and predation risk, with the latter dominating in smaller individuals and becoming less important as size increases (L'abee-Lund *et al.*, 1993; Bystrom *et al.*, 2004). Juvenile charr are confined to marginal habitats, feeding on benthic invertebrates, mostly Chironomidae (Riget *et al.*, 1986; Jonsson and Jonsson, 2001; Winfield *et al.*, 2002). Bystrom *et al.* (2004) suggested that young charr are rarely subject to density dependant factors but as individuals grow, handling times are reduced and resource limitation becomes an issue. This is because gape size is a key factor limiting foraging efficiency and larger fish move into the littoral zone to feed on larger, higher value resources (Malmquist *et al.*, 1992; Rader, 1997; Bystrom *et al.*, 2004).

Fish growth is rapid until maturity at which point the high energy costs associated with spawning cause growth to slow and size to plateau (Gullestad and Klemetsen, 1997). The energetic cost of spawning in some high latitude, low productivity regions such as Svalbard restricts spawning to every second or third year (Gullestad and Klemetsen, 1997). Age and size at maturity in charr is determined by morphotype, which in turn is determined to some extent by local habitat characteristics (Gullestad and Klemetsen, 1997; Gulseth and Nilssen, 2001; Arbour *et al.*, 2011). Larger fish are more fecund than smaller ones (Power *et al.*, 2005), so in habitats with access to ample resources either locally or via migration it may be profitable to delay maturation. In sites lacking resources and with high energy costs early maturation and spawning may be favoured. However individuals in low productivity habitats that are able to switch to higher value resources (i.e. piscivory) rapidly increase in size, are able to cope with higher energy

costs of that increased size and are more fecund. This is supported by the higher incidence of bimodality of size distribution with latitude (Griffiths, 1994).

High parasitoid loads within piscivorous charr may limit the numbers of large, mature individuals (Gallagher and Dick, 2010). Smaller morphs, feeding on the benthos picked up fewer parasitoids and developed to maturity. In this instance dwarfism may be a response to a high probability of parasitoid infection rather than simply a product of low resource availability. Given the higher cost of spawning for females (Wooton, 1985) it is energetically more efficient for them to mature as older, larger individuals and a higher first spawning age in females fish has been observed in some populations (Gulseth and Nilssen, 2001).

Arctic charr can be relatively long lived, sometimes attaining ages in excess of 30 years, with the age of maturity differing between morphs (Jonsson *et al.*, 1988; Gullestad and Klemetsen, 1997; Jonsson and Skulason, 2000). Larger morphs tend to mature later at around 8yrs; in contrast mature individuals from dwarf populations have been reported as early as age 2 with fork lengths of as little as 7cm (Jonsson *et al.*, 1988; Klemetsen *et al.*, 2003a). Associated with this more rapid development, smaller morphs tend to die earlier (Wooton, 1985; Gulseth and Nilssen, 2001).

8.1. i) **Arctic charr flow preferences**

Intraspecific competition determines distribution within streams for many species of salmonids (e.g. Nielsena, 1992; Nakano and Furukawa-Tanaka, 1994; Nakano, 1995).

Dominant fish defend profitable territories with others relegated to sub-optimal sites or free swimming foraging (Nielsena, 1992). Profitable territories have a combination of food supply and flows that optimize net energy intake (NEI) at low swimming cost (SC) and tend to be at the head of pools/ deeper water areas (Guensch *et al.*, 2001). No study has focused on territorial competition between stream dwelling Arctic charr but interactions related to dominance hierarchies have been observed within the species (Overli *et al.*, 1998; Overli *et al.*, 1999). It therefore seems reasonable to assume that charr will behave in a manner similar to related species, most preferring to utilize pools above other stream habitat patches.

8.1. ii) **Why are they of interest in Arctic systems?**

The optimum temperature for growth of Arctic charr is around 16°C (Larsson and Berglund, 1998; Lehtonen, 1998; Larsson, 2002) with growth suppressed above 18°C (Lyytikäinen *et al.*, 2002). Arctic charr prefer lower temperatures, between 9.2°C to 11.5°C opting to maximize growth efficiency rather than overall growth rate (Larsson, 2005; Larsson and Berglund, 2005). This behavioural adaption to low productivity habitats, along with their high tolerance for low thermal conditions has led to their predominance in many high latitude systems (Baroudy and Elliott, 1994; Klemetsen *et al.*, 2003a). Arctic charr are often the only fish species present in high latitude freshwater systems (Gulseth and Nilssen, 2001) occupying the top trophic level, but can also extend to occupy all consumer levels a food chain through resource polymorphism (e.g. Malmquist *et al.*, 1992) potentially increasing its stability. As often the largest and

sometimes the only aquatic prey species charr can also make a significant contribution to the diet of predatory birds such White Tailed Eagles (Wille and Kampp, 1983).

Marine subsidies brought back into freshwater systems by anadromous salmon can have significant impacts on growth and productivity of riparian habitats (Helfield and Naiman, 2001). Despite being less dramatic than the large numbers of Coho or Sockeye salmon carcasses that litter many South Eastern Alaskan river beds, the seasonal migration of Arctic charr may still provide a significant subsidy to certain Arctic systems; especially when the ultra-oligotrophic nature of some of these systems is considered (Gulseth and Nilssen, 2001). There may also be a small but important subsidy of lake epibenthic ecosystems by resident fish migrating from relatively productive littoral summer habitats.

As well as a key role in ecosystem function the Arctic charr is economically very valuable, supporting many Northern fishing communities, highly prized for its strong flavor (Wrona *et al.*, 2006; Wrona *et al.*, 2005; Johnson, 1984).

8.1. iii) **Rationale behind this study**

Many northern species are threatened by the recent temperature increases associated with global climate change (e.g. Mcdonald *et al.*, 1994; Harte *et al.*, 2004; ACIA, 2004; Callaghan *et al.*, 2004). Arctic charr are particularly vulnerable to climate warming due to their low thermal growth optima and low resistance to higher water temperature (Baroudy and Elliott, 1994; Lehtonen, 1998; Larsson, 2005; Elliott and Elliott, 2010). Increasing temperatures will reduce fitness, making fish more susceptible to predation and parasites.

Not only will warmer average water temperature reduce the range occupied by the Arctic charr's potential niche, northward range expansion by other anadromous species of salmonids will restrict charr to less favourable habitat (Langeland *et al.*, 1991; Nakano, 1995; Larsson, 2005). In the absence of other fish species trophic polymorphism has led to several distinct sub-populations of charr, some of which appear to be genetically distinct (Skúlason *et al.*, 1996; Jonsson and Skúlason, 2000). In multi species communities charr tend to be epibenthic, out competed in littoral zones by trout (Langeland *et al.*, 1991). If restricted to this one niche across the entire range much of the present genetic and subsequent phenotypic variability within the species may be lost.

In systems connected to the sea, warming temperatures may lead to species replacement, but trophic dynamics and local diversity may well be maintained. However in systems lacking corridors of migration, ecological function will be disrupted as coldwater species are lost but not replaced. The low upper thermal limit for Arctic charr makes systems where they dominate particularly susceptible to this trajectory under a warming climate.

The purpose of this investigation was to ascertain the extent, population size and age structure, habitat use and feeding niche of a previously unstudied population of Arctic charr in Northern Sweden. The overall aim was to estimate the impact of this charr population on the functional ecology of the system as whole and asses its potential susceptibility to predicted climate change.

8.2 Methodology

8.2. i) **Study site**

Data for this investigation was collected on the 13th and 14th of August 2009 in the two main channels of the lower braided section of Kårsavagge above Bajimus Gorsajari, the first lake in the system (Figure 3.4 and 3.5). This area of the system was chosen as the lakes are known to hold a small head of fish and there was anecdotal evidence that some fish utilized the lower braids. The justification for this investigation was to determine the size of the fish population within the lower braided section and the extent to which they utilized the habitat of these two contrasting channels. The South West braid (C1-C10) is fed predominantly by a combination of glacier melt waters and snowmelt, whereas the adjacent North-East braid (A1-A10) is groundwater fed. Both channels are unregulated and flow into the lake.

8.2. ii) **Sample collection and processing**

The main channel of the South West braid was deep (min ~0.5m) and fast flowing ($>0.60 ms^{-1}$) and it was deemed too dangerous to electrofish so quantitative sampling was restricted to the East braid. The entire 756m of the East braid (A1-A10) was divided into 12 sample reaches. Each reach was electrofished using a back pack mounted ELT60-IIH Honda electro fisher. Stop nets positioned at the top and bottom of each sample reach isolated the fish within, and the electro fisher operator moved from the downstream end to the upstream sweeping the anode back and forth below the water surface. Two sample

runs were made in each reach. Upon capture fish were transferred to a within stream holding pen away from the sampling reach. Temperature, resistivity, conductivity, dissolved oxygen concentration, total dissolved substances and pH were measured in the middle of each sample reach with a Myron Ultrameter II.

Prior to measuring on site each fish was anesthetized in a solution of 40mg L^{-1} clove oil, made up by mixing 5L of stream water with 2ml of a 1:9 mix of clove oil and ethanol following Woody *et al.*, (2002). Measurements (fork length and weight) were taken for each of the 204 fish captured. One hundred individuals representing the range of sizes encountered had 3 scales removed for ageing. Non regenerated scales were removed from just behind the midline and just above the lateral line and placed between a cover slip and a slide. Tweezers were rinsed in ethanol between each sample.

In order to carry out analysis of Arctic charr diet 102 fish were randomly chosen to be gut flushed following. A flexible length of PVC pipe was attached to a 2ml syringe and used to inject water into the mouth of an anesthetized fish. The stomach contents were washed out into a small whirl pack bag and preserved in 70% ethanol. After measurement all fish were retained in a pen within the channel and released once they had fully recovered.

Benthic invertebrates within the lower braided section (Figures 3.4 and 3.5) were investigated through semi-quantitative sampling on one date in 2009 to inform a study of the diet preferences of the Arctic charr population. The ground water channel (East channel) was sampled on 13th August 2009, the glacial channel (West) the 14th August 2009. Each channel was sampled at 3 points (A2, A5 and A8; C1, C5 and C7 see figure 3.3). Each sample incorporated three $0.1m^2$ Surber sample replicates (250 μm mesh) and

one run with a 0.1m^2 (250 μm mesh) pond n*et al*ong a 5m length of the each bank following forceful disturbance with a boot (as in Barbour *et al.* 2006).

Three sites were identified along the length of both sample channels to categorize the habitat of each (A2, A5 and A8; C1, C5 and C7 see Figure 3.4). At each site the benthic, substrate, suspended sediment concentration (SSC) and measures of channel form were taken. Three Surber and one kick sample were collected and preserved in 70% ethanol to investigate species composition of the benthic macro invertebrate community. Substrate size was determined by measuring the b-axis of 100 substrate particles. Particles were selected by walking a transect across the channel and picking up the first particle contacted by each footfall following Gordon *et al.* (2004). The dry weight of Whatman 40 filter papers were recorded after drying overnight at 60°C. These were used to filter three 500ml samples of stream water, re-dried and reweighed to determine SSC. Channel width and depth was also recorded. At each sample site and at various points along each braided channel stability was evaluated using the bottom component of the Pfankuch index (Pfankuch, 1975). Along the length of each channel a hydrogeomorphic survey was conducted adapting the following units from the classes identified by Hawkins *et al.* (1993) and Hill *et al.* (2008): run, riffle, chute, scour pool, incised bank, incised bank pool, bar, side channel, tributary input and eddy (Table 8.1).

Table 8.1 – Description of hydrogeomorphic habitat patches identified within the East channel of the lower braided section (see Figure 3.4 sites A1-A10). Habitat types taken from Hawkins *et al.*, (1993) and Hill *et al.*, (2008).

Habitat type	Description
Riffle	Turbulent flow over low gradient reach. Small Symmetrical surface ripples <1cm high moving downstream.
Chute	Turbulent flow, with higher gradient, greater bed roughness and higher velocity than riffle
Run	Non turbulent, rapid flows at low gradients.
Scour pool	An isolated pool, formed by mid-channel scouring, located in bed rock areas, channel sides and river bars.
Incised bank	Region of river bank with distinct undercut.
Incised bank pool	Incised bank with associated scour pool
Eddy	Occur at the downstream end of main channel pools and outflows, often shallow with slow moving water, occurring at the margins of a river. Typically characterized by reverse flow.
Bar	Located along a straight section of the river or on bends, often having side channels, which at higher flows often become disconnected.
Tributary Input	Region associated with input of water from connected channel
Tributary	Small channel upstream of where it enters the main channel

8.2. iii) **Data analysis methods**

a) Fish condition

Length and weight measures from individual fish were used to compute Fultons conditioning factor (K) equation 8.1 (Ricker, 1971). This relationship between Salmonid length and weight can be compared to the K chart (Table 8.2) to make an assessment of fish condition.

$$K = 100 \times {}^{W}/_{L^3} \qquad \textbf{Equation 8.1}$$

K = conditioning factor or coefficient of condition; W = weight of fish in grams (g);L = Length of fish in cm (cm)

b) Fish age

As a fish ages, growth rings (circuli) build up on its scales. During periods of faster growth (summer) circuli are spaced out, during periods of slow growth, circuli form close together creating a dark band called an annulus. It is possible to estimate the age of a fish by counting the number of annuli on a scale (Ricker, 1971). Scales removed from Arctic Charr in the field were examined under a light microscope and the annuli counted to estimate the age of each fish.

c) Diet

Gut flush samples were sorted and animal remains identified to family. Those pertaining to individuals (e.g. head capsules) were recorded as such, others were recorded as occurrences. Surber sample and kick samples were sorted and identified to family. Results from each braid were summed to give an estimate of the relative abundance of taxa within the benthic community.

The selective index recommended by Ricker (1971), Equation 8.2, was used to determine the extent to which prey taxa were preferentially selected relative to their abundance within the benthos.

$$Foraging\ index = {}^{S}/_{B} \qquad \textbf{Equation 8.2}$$

S = Percentage representation of food organism in the stomach

B = Percentage representation of same organism in the environment

Table 8.2 – Description of fish condition relating to K-Value (taken from Ricker, 1971).

K Value	Comments
1.60	Excellent condition
1.40	A good well-proportioned fish
1.20	A fair fish
1.00	A poor fish, long and thin
0.80	Extremely poor fish, a big head and a narrow thin body.

Table 8.3 - Comparison of the physical habitats within the east and west channels of the lower braided section of Kårsavagge in 2009. For relative positions see Figure 4, the east channel encompasses those channels/ sites labelled (A1-A10), the west channel encompasses those channels/ sites labelled (C1-C10).

	East Braid (A1-A10)	West Braid (C1-C10)
Main analysis sites	1) A2 - N 68.34822 E18.42535 2) A5 - N 68.34964 E18.41902 3) A8 - N 68.35368 E18.40904	1) C1 - N68.34795 E18.41830 2) C5 - N68.34962 E18.41034 3) C7 - N68.35050 E18.40600
Arctic charr population	Numerous fish were observed during a visual inspection and 204 were caught during sampling	No fish were observed in the main channel during the visual inspection, though a few individuals were seen in non glaciated tributaries
General character, width, length, depth	The total length of the channel from source to lake was 760m. Average depth at cross sections ranged from 0.22m and 0.33m, widths ranged from 8.2m close to the lake inlet and 1.8 m near the source. Highly sinuous with many meanders.	The total length of the channel from the start of the braided section to the lake was 1000m. Average depths at cross sections ranged from 0.8m to 0.5m and channel width ranged from 17 to 30m. Channel was sinuous but to a lesser degree than the east braid.
Temperature	Average water temperature within the east braid was 10.37°C with a range of 2.2°C.	Average water temperature within the west braid was 10.06°C with a range of 1.6°C.
Flow	No discharge measurements were made, however flows remained relatively constant over the survey period with velocities averaging at 0.39ms^{-1} with a range of 0.20ms^{-1}.	No discharge measurements were made, however observed flows appeared more variable than those of the east braid over the survey period with velocities averaging at 0.60ms^{-1} with a range of 0.37ms^{-1}.
Substrate	Average b-axis : 0.83 D50 b-axis : 0.36 Sims Div : 0.86	1.99 1.48 0.84
	t-test revealed significant differences between bed substrate composition of the East and west braids (t = 4.205, p<0.001, d.f. = 17)	
Suspended sediment	Low turbidity. Average SSC of 1.4mgl-1 during the survey. Visual inspection over two sampling seasons suggests stream conditions reflect average conditions in the east braid.	Highly turbid. Average SSC of 8.6mgl-1 during the survey. T-test revealed significant differences between East and west braid (p<0.001).Maximum observed SSC in this stream over both sampling seasons was 132mgl-1.
Benthic Invertebrates (Based on 3 surber	Total taxa richness 7 Total abundance 40 Proportion Chironomidae 0.72	Total taxa richness 5 Total abundance 40 Proportion 0.8

and 1 kick sample per site, i.e. A1)		Chironomidae
Pfankuch index scores	Indicative of a relatively stable stream channel. Classed as a good stream with an average index score of 80.	Generally classed as a poor stream with all index scores above 115, a average of 127.3

8.3 Results

The conditions within the glacial fed South Western braid prohibited electrofishing, so detailed analysis of Arctic charr ecology and habitat use was based solely on data collected from the groundwater fed North Eastern braid. A visual inspection of the South Western braid was undertaken to assess its potential Charr population but no fish were observed within the main channel. It has been assumed that during the period of this study the main channel of the glacial fed South Western braids did not constitute significant habitat for Arctic charr. A comparison between the two channels is made in Table 8.3.

8.3. i) **Arctic charr from the East braid**

In total 204 fish were captured with an average length of 127mm (range 55mm to 194mm) and an average mass of 23g (range 2g to 76g). The relationship between fork length and weight was comparable with that found in studies of other Arctic charr populations (Figure 8.2)

$$Log\ M = 2.79\ (Log\ L) - 10.58$$ **Equation 8.3**

M = Mass (g); L = length (mm).

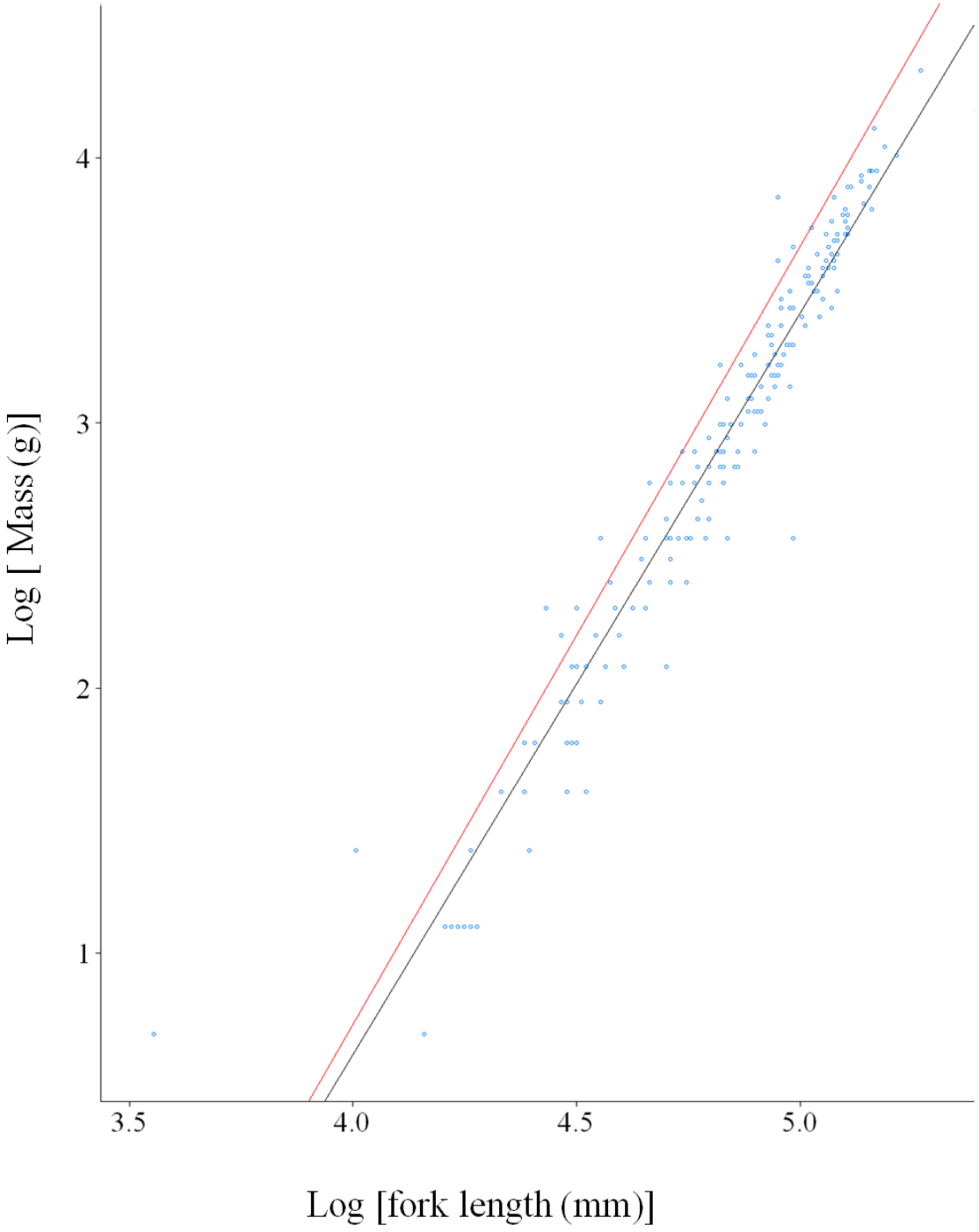

Figure 8.2 - The relationship between log (mass) and log (fork length) of all the sampled Arctic charr from Kårsavagge, n= 201. Black line is the best fit line described by equation 8.3, red line relationship reported in Malmquist *et al.*, 1992 of a dwarf benthivorous morph.

A length frequency plot of the data (Figure 8.3) illustrates a unimodal distribution. The population consists of at least five age classes, 0+ - 4+ estimated by counting annuli from the scales of selected individuals (n=100) (Figure 8.4). These individuals of known minimum age were used to investigate size, weight and fitness differences between age classes. There were significant differences in length (ANOVA, $F_{1, 98} = 288.7$, $p<0.001$) and weight (ANOVA, $F_{1, 98} = 224.7$, $p<0.001$) between cohorts; but no significant difference was found in conditioning factor (ANOVA, $F_{1, 98} = 0.43$ $p = 0.51$) (Table 8.4 & Figure 8.4). The majority of aged fish (57%) were classed as "poor, long and thin" with 29% classed as "fair" and only 6% classed as "good" or "excellent". This corroborated with the population as a whole which had an average conditioning factor of 0.97, with 64% of individuals caught classed as poor or extremely poor.

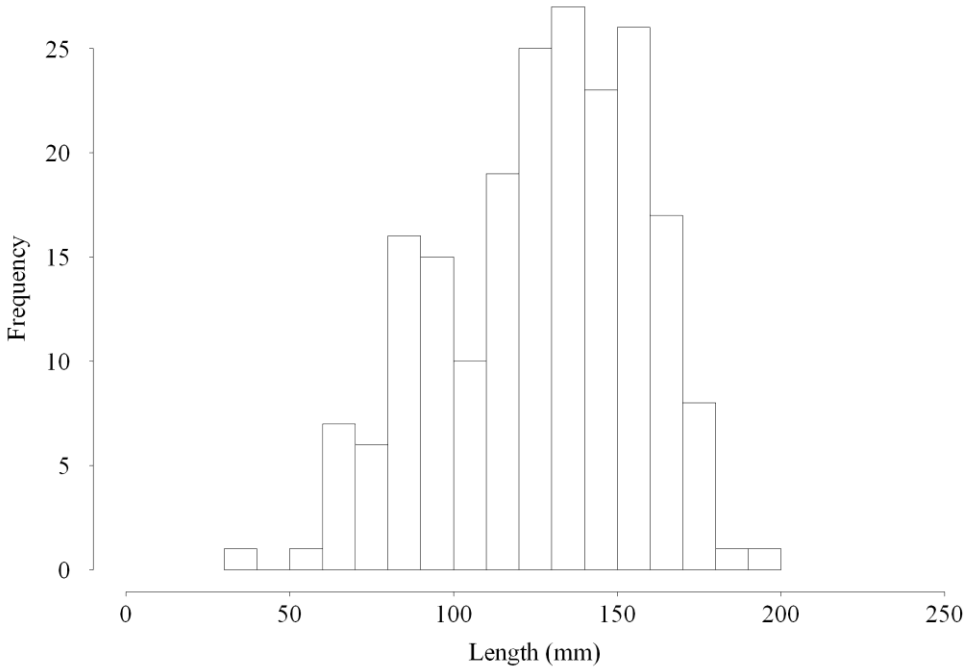

Figure 8.3 - Length frequency diagram for all Arctic charr sampled in the eastern channel (A1-A10) of the lower braided section of Kårsavagge, n = 201.

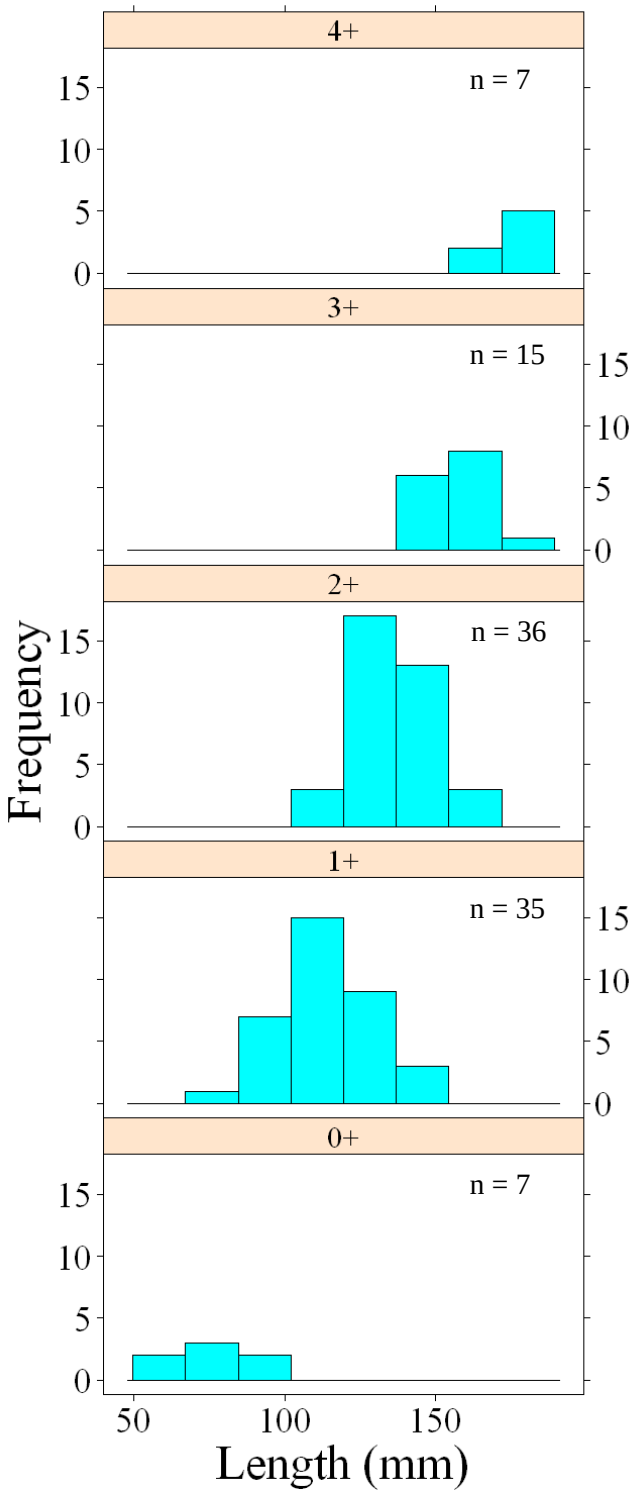

Figure 8.4 - Length frequency plot of the Arctic charr from Kårsavagge identified as belonging to different cohorts through analysis of scale samples: 0+ (n = 7), 1+ (n = 35), 2+ (n = 36), 3+ (n = 15) and 4+ (n = 7);

Table 8.4 - Descriptive statistics for Arctic charr separated into different cohorts; *x* = mean, numbers in brackets ( ) = Standard deviation.

Age	N	Length (mm)		Mass (g)		Condition factor	
		x	*range*	*x*	*range*	*x*	*range*
0+	7	76.4 (*15.2*)	55-95	4.6 (*1.9*)	2.0-7.0	1.10 (*0.60*)	0.75-2.40
1+	35	113.6 (*16.3*)	80-146	14.7 (*6.2*)	6.0-37.0	0.98 (*0.20*)	0.41-1.52
2+	36	137.0 (*13.4*)	106-165	25.4 (*8.5*)	13.0-47.0	0.96 (*0.17*)	0.75-1.68
3+	15	157.9 (*6.8*)	151-173	37.7 (*6.2*)	30.0-49.0	0.95 (*0.08*)	0.79-1.05
4+	7	174.1 (*7.2*)	161-184	52.6 (*6.3*)	41.0-61.0	0.99 (*0.08*)	0.88-1.13

Table 8.5 - Hydraulic habitat encountered within different sample reaches of the east channel of the lower braids. (), Numbers in brackets, denotes number of fish caught in that habitat. Ru (run), Ri (riffle), In (tributary input), Ch (chute), IB (incised bank), B (bar), SP (scour pool), R (rocks), IbP (incised bank pool), Tri (tributary), Ed (eddy).

Reach	Ru	Ri	In	Ch	IB	B	SP	R	IbP	Tri	Ed
One	3 (-)	9 (-)	1 (-)	4 (*3*)	1 (-)	11 (-)	5 (*8*)	1 (-)	0 (-)	1 (-)	0 (-)
Two	1 (*1*)	9 (*2*)	1 (-)	4 (-)	1 (-)	6 (-)	2 (*7*)	1 (-)	4 (*7*)	1 (-)	0 (-)
Three	5 (*2*)	7 (*6*)	1 (-)	3 (-)	1 (*3*)	5 (-)	1 (*19*)	0 (-)	4 (-)	1 (-)	1 (*1*)
Four	2 (*1*)	10 (-)	0 (-)	4 (*1*)	2 (-)	8 (-)	7 (*25*)	0 (-)	1 (-)	1 (-)	0 (-)
Five	2 (-)	9 (*3*)	0 (-)	5 (*1*)	1 (-)	4 (-)	5 (*20*)	0 (-)	2 (*11*)	2 (-)	0 (-)
Six	2 (-)	10 (*4*)	0 (-)	3 (-)	2 (*4*)	5 (-)	12 (*15*)	0 (-)	1 (*26*)	7 (-)	0 (-)
Seven	0 (-)	0 (-)	0 (-)	0 (-)	0 (-)	1 (-)	2 (*8*)	0 (-)	0 (-)	1 (-)	0 (-)
Eight	2 (-)	3 (*1*)	1 (*1*)	0 (-)	0 (-)	0 (-)	1 (*2*)	0 (-)	0 (-)	0 (-)	0 (-)
Nine	2 (-)	3 (-)	0 (-)	1 (-)	0 (-)	2 (-)	2 (*4*)	0 (-)	0 (-)	2 (-)	0 (-)
Ten	2 (*3*)	2 (*2*)	0 (-)	4 (*3*)	1 (-)	3 (-)	1 (-)	0 (-)	0 (-)	2 (-)	0 (-)
Eleven	1 (-)	5 (*2*)	0 (-)	3 (-)	1 (*2*)	5 (-)	1 (-)	0 (-)	0 (-)	2 (-)	0 (-)
Twelve	2 (-)	11 (*6*)	1 (-)	6 (-)	0 (-)	4 (-)	4 (-)	0 (-)	0 (-)	1 (-)	0 (-)

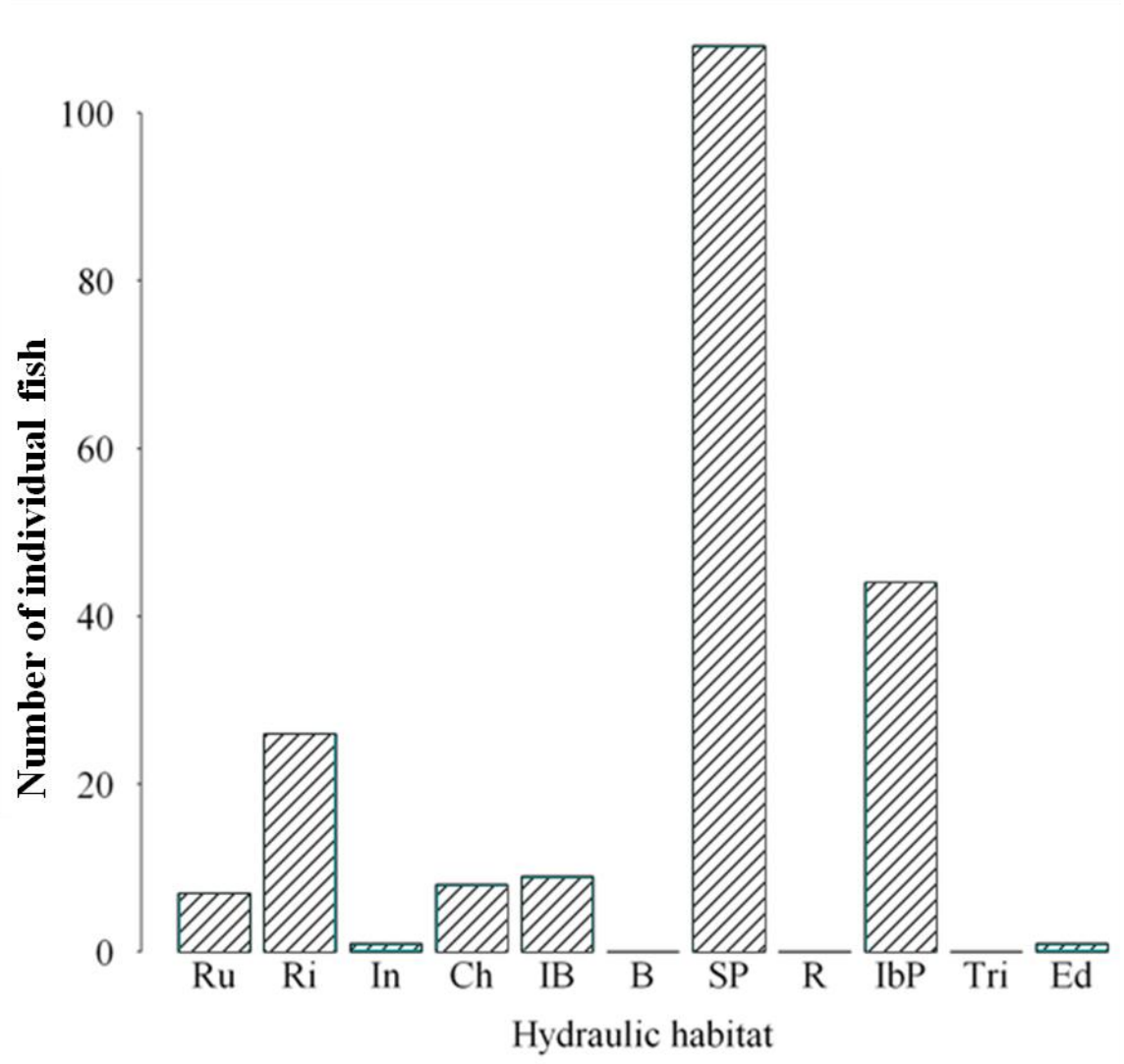

Figure 8.5 – Number of Arctic charr captured from identified hydrogeomorphic habitat patch types from within the east channel of the lower braided section of Kårsavagge. Ru (run), Ri (riffle), In (tributary input), Ch (chute), IB (incised bank), B (bar), SP (scour pool), R (rocks), IbP (incised bank pool), Tri (tributary), Ed (eddy).

8.3. ii) **Stream hydraulic habitat**

Morpho-hydraulic habitats and water surface flow patterns were mapped following table 1 and the results are summarized in Table 8.5. The majority of Arctic charr recorded were associated with pool habitats (Figure 8.5). In total 75% of the captured fish came from pools, either scour pools in the channel bed (53%) or the more complex habitat of

pools underneath incised banks (22%). Incised banks without associated pools accounted for only nine individuals (4%). The Arctic Charr in this stream appear to be displaying a habitat preference. Riffles, the most common hydraulic habitat (73 individual occurrences, 27% of total habitat patches recorded) only accounted for 13% of the total Charr population. In contrast, forty three scour pools yielded 53% of the overall catch.

8.3. iii) **Stomach contents of captured Arctic charr**

One hundred and two Arctic charr were gut flushed for diet analysis of which 12 were empty. Of the 89 fish containing identifiable material, 73 could be aged from scale samples. In order to assess feeding habits within different sized fish, size classes were drawn up based upon the length frequency distribution, these were 0-70mm, 71-90mm, 91-110mm, 111-130mm, 131-150mm, 151-170mm, 170+mm. There is no assumption made that these size classes correspond to age classes.

In total, 68% of prey items identified from stomach contents were aquatic in origin with the remaining 32% terrestrial organisms/ adult Diptera. No evidence of piscivory was found. Chironomidae were the dominant taxa recorded from gut samples with larvae and pupae accounting for 61% of prey abundance. The next most common prey taxa were adult mosquitoes and other adult Diptera, each accounting for 15% (Figure 8.6). When the proportionate representation of different prey taxa in the gut samples was compared between different size classes of fish, significant differences were observed for Chironomidae (ANOVA, $F_{6, 82} = 2.74$, $p = 0.018$) . Significant differences were also found when prey taxa were grouped according to postulated source, i.e. terrestrial taxa,

aquatic taxa and adult Diptera. Larger fish tended to have a higher proportion of gut contents made up by adult Diptera (ANOVA, $F_{6, 82} = 2.33$, $p = 0.040$) and smaller fish had a higher proportion of made up by within stream invertebrates (ANOVA, $F_{6, 82} = 2.47$, $p = 0.030$) (Figure 8.7). No significant difference in the proportion of terrestrial taxa consumed by different size classes was found. There was no significant difference between the proportions of different prey taxa in the gut contents of fish from different conditioning factor classes.

Table 8.6 – Foraging ratio's associated with taxa encountered in Arctic charr guts. Ratios computed following equation 8.2, percentage occurrence of prey organism in the environment taken as the percentage abundance from pooling benthic samples taken at sites A2, A5 and A8.

Benthos	Foraging Ratio
Chironomidae	1.03
Chironomidae pupae	1.58
Simuliidae	6.87
Simuliidae pupae	1.25
Coleoptera larvae	0.26
Coleoptera	1.25
Trichoptera	0.03
Oligochaeta	0.25

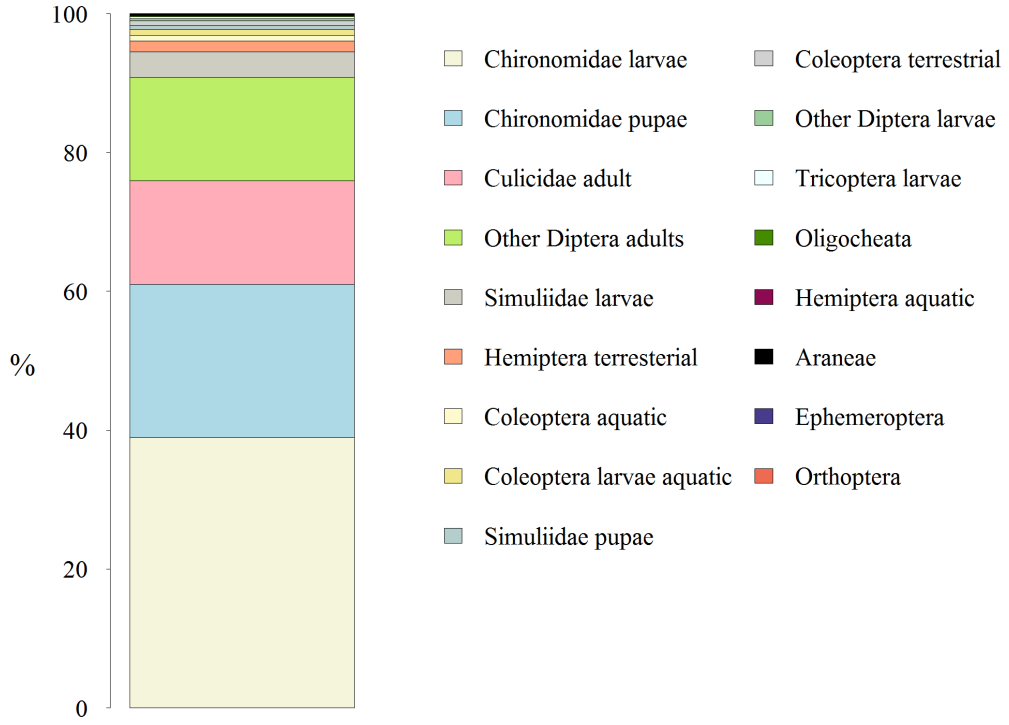

Figure 8.6 – Proportion of all prey encountered within Arctic charr stomachs. Calculated by pooling data from all gut flush samples containing material (n= 89). 102 Arctic charr sampled from Kårsavagge of which 13 fish had empty stomach.

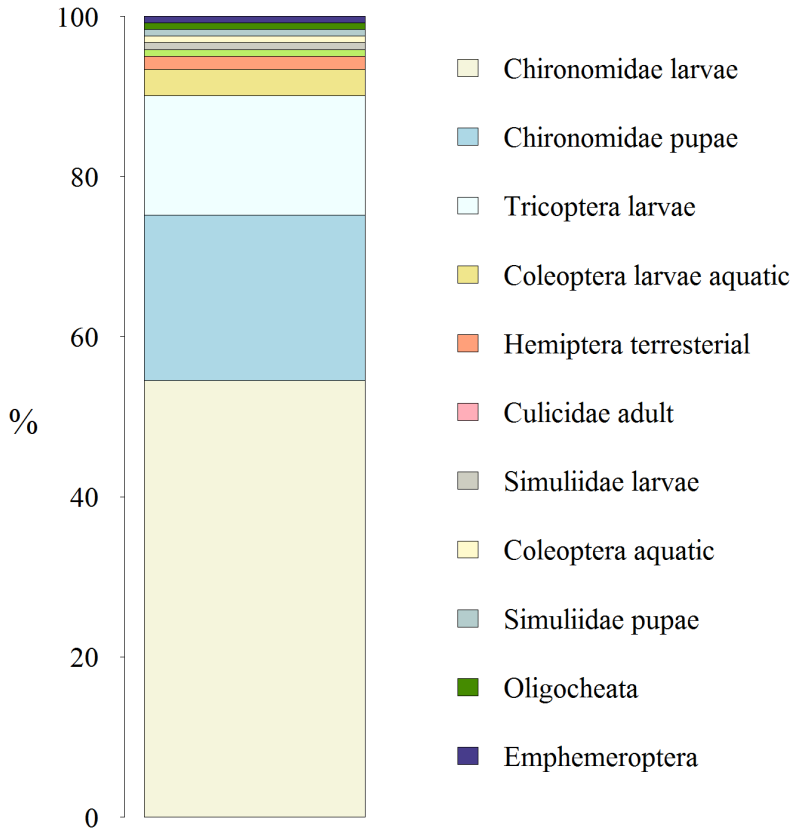

Figure 8.7 - Proportion of different invertebrate taxa encountered in benthic samples from the east channel of the lower braided section of Kårsavagge. Chart produced by pooling data from each of the three sample sites: A2, A5, A8 (at each sample site 3 replicate surber samples and one kit net exploration of both banks was carried out).

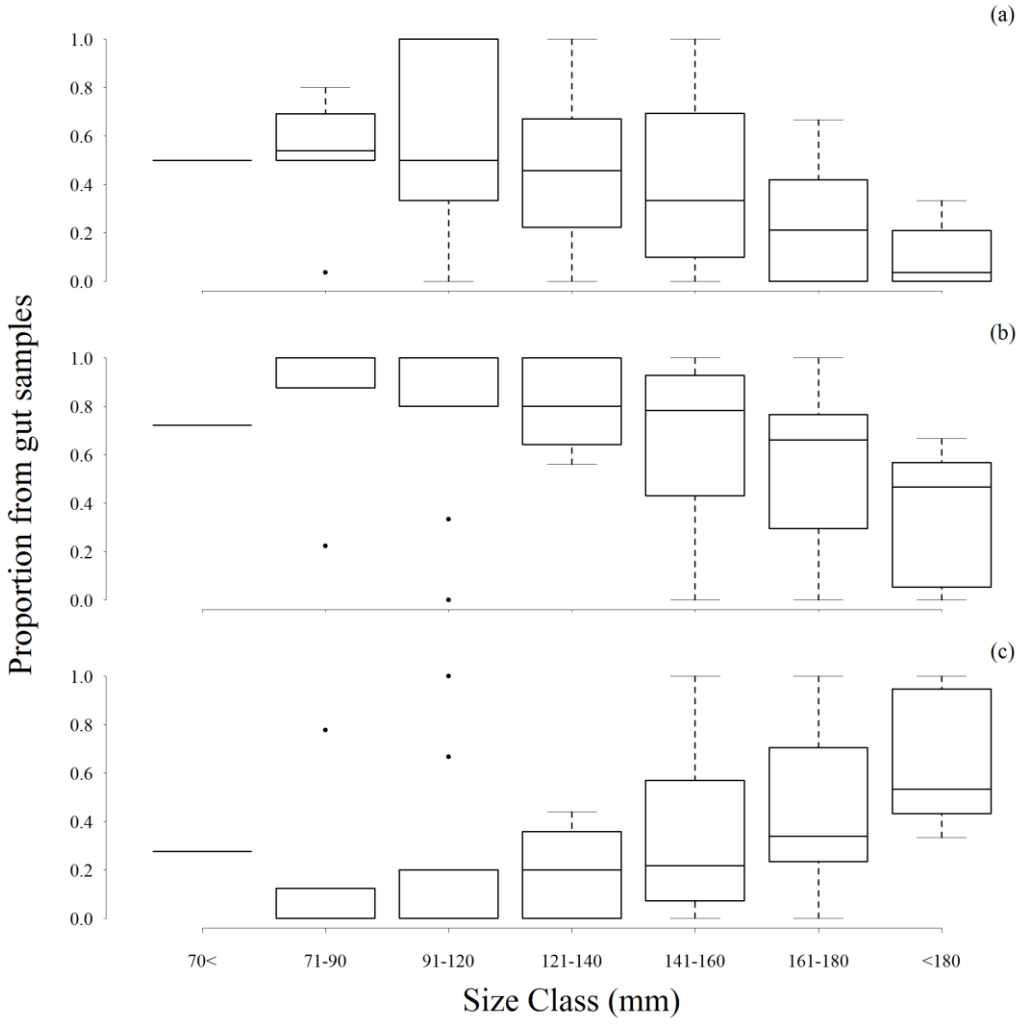

Figure 8.8 - Proportion of different prey recorded in gut samples of charr of different size classes: 70< (n = 1), 71-90 (n = 5), 91-120 (n = 9), 121-140 (n = 11), 141-161 (n = 23), 161-180 (n = 34), <180 (n = 6); Total = 89. (a) Chironomidae larvae, (b) benthic stream invertebrate larvae, (c) adult Diptera.

When the proportion of aquatic prey species are compared to the proportions of taxa recorded from benthic samples it appears that certain taxa are taken preferentially (Figure 8.6 & Figure 8.7). Foraging ratios associated with different taxa (Table 8.6) suggest that Simuliidae occur far more frequently (foraging ratio of 6.87) in guts than in the benthos. Despite the dominance of Chironomidae in the gut flush samples this seems to reflect their numerical dominance within the local habitat (Figure 8.7) rather than positive selection. Unsurprisingly, larger species and those with more developed defensive architecture or carapaces requiring the greatest handling time (e.g. Trichoptera and Coleoptera larvae) occur less frequently in guts than would be expected and consequently have very low foraging ratios.

8.4 Discussion

8.4. i) **Charr morphotype**

The landlocked population within the Eastern braid of the lower braided section of Kårsavagge is best described as the dwarf morphotype given their small size, length to weight relationship and gut contents. Informal interviews with locals suggests that a large piscivorous morph does exist but it is presumed to be confined to lake Bajimus Gorsajvri, as no larger morphs were observed during either sampling season. Riget *et al.* (2000) suggest that lake size plays an important role in determining the range of charr morphotypes displayed and lake Bajimus Gorsajvri is large enough on their scale (max depth >20m) to accommodate two body morphs along a bimodal size distribution. Arctic Charr are noted for their ecological flexibility both in terms of behavioural and

morphological adaptations (Gulseth and Nilssen, 2001; Klemetsen *et al.*, 2003a). High latitude populations with access to the sea usually contain at least two body morphs a smaller, resident (non-anadromous) morph and a larger anadromous morph which spends summer feeding at sea (Griffiths, 1994). The morphological variation within sympatric, landlocked populations of Charr can be equally great (Klemetsen *et al.*, 2003a; Skúlason *et al.*, 1996). Four distinct body morphs, large benthivorous (Fork length (F.L.) 20-50cm), small benthivorous or dwarf (F.L. 7-15cm), piscivorous (F.L. 25-60cm) and planktivorous (F.L. 15-22cm) were found within Lake Thingvallavatn, Iceland (Malmquist *et al.*, 1992) and similar body variants have been observed across the arctic (Riget *et al.*, 2000; Gulseth and Nilssen, 2001; Gallagher and Dick, 2010). The high phenotypic and ontogenetic plasticity of this species has enabled it establish populations on every major landmass within the Arctic Circle.

The oldest class recorded from scale samples in this study was 4+, less than would be expected as Arctic charr populations frequently contain fish over 15 years of age, with some individuals exceeding 30 years; first spawning generally ranges from 2 to 10 years of age (Skúlason *et al.*, 1996; Gulseth and Nilssen, 2001). Despite the more rapid maturation of smaller body morphs, males can mature by age 2 but females still tend to take up to 3yrs to reach maturity, this max age is still lower than would be expected (Skúlason *et al.*, 1996; Klemetsen *et al.*, 2003a). Difficulties have been noted by several authors in determining accurate estimates of age from scales of cold, slow growth salmonids (Jensen and Ove Johnsen, 1982; Baker and Timmons, 1991; Zymonas and Mcmahon, 2009; Horká *et al.*, 2010) with charr particularly difficult as they tend to occupy the coldest habitats and have been noted to cease formation of recognizable

growth zones after maturation (Nordeng, 1961). However the alternative, counting annuli from otoliths used in most studies of large populations (Baker and Timmons, 1991; Radtke *et al.*, 1996) is lethal and was not considered in this investigation given the potential sensitivity of this previously unrecorded population. As such, rather than an absolute age, estimates from scale samples should be seen as a minimum age, or age at first spawning. This 'fuzzy aging' may account for the predominance of 1+ and 2+ cohorts within the aged sample, however the age distribution is similar to that reported by Witkowski *et al.*, (2008) from a similar sized stream on Svalbard.

The low number of small (<70mm) fish may reflect poor recruitment in recent years or possibly the inadequacy of electrofishing for sampling smaller individuals which experience a reduced effect, tend to by more cryptic and often reside deep within marginal vegetation (Zalewski, 1983; Zalewski and Cowx, 1990; Dolana and Mirandaa, 2003).

Fulton´s conditioning factor score implies that fish within Kårsavagge are generally "poor" undernourished with few individuals reaching "good" or higher status. This is not unexpected for a population of wild salmonids in a relatively low productivity Arctic stream (Gullestad and Klemetsen, 1997). Social status, defined by competitive interactions determines which fish occupy optimal feeding stations in most stream dwelling salmonid species (Nielsena, 1992; Guensch *et al.*, 2001; Martinussen *et al.*, 2010). Those fish established as low rank often exhibit lower consumption rates even in the absence of higher ranked conspecifics (Gilmour *et al.*, 2005). In a low productivity environment, competition for resources intensifies and only dominant fish obtain high

resource yields; the majority will be consigned to forage in sub-optimal habitat. As a result condition factors are not high.

8.4. ii) **Why did the West braid hold no fish?**

The West braid supported no Arctic charr, however further investigation revealed small numbers of fish within snowmelt/ groundwater fed tributaries. In contrast, fish appeared to prefer the main channel of the East braid, as lower numbers were caught in the upper tributaries. This pattern of fish distribution is likely to reflect the harsher conditions within the main channel of the South West braid. A major portion of flow in the South West braid is glacially sourced, hence its' significantly higher SSC. The significantly larger caliber of bed material may also reflect this glacial influence as smaller material is mobilized and transported in the higher flows. Pulses of high SSC have been shown to negatively impact populations of salmonid fish (Lake and Hinch, 1999; Guensch *et al.*, 2001; Bilotta and Brazier, 2008; Lazar *et al.*, 2010). The higher turbidity reduces visual acuity and thus catch efficiency, feeding hierarchies are disrupted and the physical attrition of the suspended particles can damage gill rakers (Berg and Northcote, 1985; Lake and Hinch, 1999; Shaw and Richardson, 2001; Korstrom and Birtwell, 2006). SSC can be lethal at extremely high values (Bilotta and Brazier, 2008) and any Arctic charr resident within the South West braid would be subjected to pulses of high SSC. Maximum SSCs recorded in the West braid are an order of magnitude greater than any during this study period. It is likely that the West braid provides a corridor between overwintering regions and more productive habitats when SSC concentrations are higher,

and is occasionally exploited as a foraging habitat in so called ‘windows of opportunity’ when glacial influence is reduced (Milner *et al.*, 2001b).

8.4. iii) **Habitat selection by Arctic charr**

The main Arctic Charr habitats within the North East braid were scour and incised pools. They yielded 75% of the total catch and had a significant positive correlation with relative fish abundance per reach. Certain microhabitats within pools offer a flow regime and prey resource density that maximizes net energy intake (NEI) and as a result salmonid taxa tend to utilize these rather than faster flowing regions of low NEI (Bohlin, 1977; Fausch, 1984; Guensch *et al.*, 2001). Pools, especially those with over hanging banks also provide shading and protection from terrestrial predators. Grant and Krammer (1990) illustrated territoriality limits population density in salmon parr within riffles; assuming that stream dwelling Arctic charr form similar dominance hierarchies (e.g. Overli *et al.*, 1998; 1999) the number, density and distribution of high value foraging stations may play a significant role on maximum fish density within a reach. Despite having a relatively stable channel itself, the East braid is cited in a region of the river system with the potential for rapid channel migration. If the number and density of key foraging habitats is altered by interaction with a migrating channel of the Western braid it could have severe impacts on the profitability of the braids as a whole as an Arctic charr habitat.

Arctic charr undergo seasonal migrations from winter refuges to summer forage sites (Klemetsen *et al.*, 2003a). In anadromous populations, older (4+) fish spend several

weeks at sea, whereas landlocked or resident populations move into more productive but exposed regions of lakes or rivers (Radtke *et al.*, 1996; Babaluk *et al.*, 2001; Gulseth and Nilssen, 2001; Svenning and Gullestad, 2002; Witkowski *et al.*, 2008; Eloranta *et al.*, 2010). In Kårsavagge, the braided streams form the high productivity (relative to the oligotrophic lake Bajimus Gorsajvri) forage grounds with the population retreating into the lake or deeper marginal pools to avoid winter mortality. The extent to which the population utilizes flood plain overwintering sites is of interest as it could influence acquisition of key forage sites the following season. Retreat into the lake will avoid freezing but increases the chance of predation by picivorours morphs. Siikavuopio *et al.* (2009), not only demonstrated a high overwinter survival of Arctic Charr in an ice covered Norwegian groundwater stream but also that they continued to grow. Thermal monitoring in Kårsavagge shows that at least one pool (A4) connected to the East braid remains unfrozen throughout winter. Assuming oxygen concentrations do not dip below lethal concentrations this pool would provide an ideal overwintering habitat and may allow access to high quality forage grounds earlier than those overwintering in the lake. Siikavuopio *et al.*, (2009) transported and contained their population within the stream, so the extent of within stream overwintering in natural populations has yet to be investigated. However, Bohlin (1977) demonstrated that incumbent sea trout (*Salmo trutta*) parr were more successful in competitive interactions compared to introduced fish and if this holds true for Arctic charr, early acquisition of an optimal feeding station would confer a significant competitive advantage.

Analysis of the diet of different size classes of charr illustrates that adult Diptera and terrestrial invertebrates form a significantly greater proportion of total consumed prey in

larger size classes. A similar pattern was reported in rainbow trout (Oscoz *et al.*, 2005), coho salmon (*Oncorhynchus kisutch*) (Nielsena, 1992), white-sported char (*Salvelinus leucomaenis*) and Dolly Varden (*Salvelinus malma*) (Nakano and Furukawa-Tanaka, 1994). This may relate to shifts in habitat or gape limitation associated with ontegeny as prey species in nursery habitats tend to be small and benthic (Rader, 1997; Steingrímsson and Gíslason, 2002). It may also reflect competition between cohorts, with older, larger fish being better competitors. The dietary results of charr from the East braid appear to suggest feeding hierarchies similar to those observed in stream dwelling salmonids, rather than the developmental diet shifts recorded in lacustrine charr. Dominance hierarchies have been noted in Arctic char (Overli *et al.*, 1998; 1999) and similar hierarchies in other salmonid taxa have led to differential diet composition between different ranks (Nielsena, 1992; Nakano and Furukawa-Tanaka, 1994; Nakano, 1995). Nielsena (1992) observed that the feeding strategy of juvenile coho salmon was determined by their rank. Aggressive, dominant fish defend foraging stations that maximize access to drifting prey whilst keeping energetic costs as low as possible (Guensch *et al.*, 2001), sub-dominants access drift from sub optimal sites with other fish labeled 'non-hierarchical floaters' foraging opportunistically over a wider habitat. Growth rates varied with Dominants > sub-dominants > floaters. The greater proportion of adult Diptera in the diet of larger charr in this study may reflect the greater access these individuals have to aerial prey species and others delivered in the drift. Conversely, it could simply reflect an increased efficiency of larger individuals in a population of opportunistic foragers to make use of this seasonal pulse of adult mosquitoes through reduced handling time.

8.4. iv) **Aquatic prey selectivity**

Diptera adults and larvae make up the bulk of Arctic charr diet, with the very low proportion of other taxa such as Hemiptera and arachnids suggesting that these taken opportunistically. Few predators specialise in one type of prey, however most are expected to show discretion when selecting prey, maximising net energy intake (NET) by efficient use of available resources (Stephens and Krebs, 1986; Begon *et al.*, 2002; Weber *et al.*, 2010). That may mean concentrating on the highest energy prey species, but trade-offs relating to prey handling time (due protective adaptations) or encounter rate (due to rarity) may reduce the effectiveness of this strategy. The strongest positive selection as determined by foraging ratio was for Simuliidae larvae, possibly due to the high heterogeneity of benthic invertebrate distribution, especially given the low numbers of Simuliidae encountered. Arctic charr are described in most texts as generalist predators and are known for niche and trophic plasticity (Fraser *et al.*, 1998; Knudsen *et al.*, 2006; Amundsen *et al.*, 2008; Arbour *et al.*, 2011; Eloranta *et al.*, 2011) so this apparent positive selection of Simuliidae larvae may simply be an artefact of sampling strategy. If, as suspected, foraging stations within pools on the cusp of riffles are prime habitat for charr and those riffles in term are prime habitat for Simuliidae (Horne *et al.*, 1992; Malmqvist, 1994; Malmqvist and Sackmann, 1996) then the encounter rate may be much greater than anticipated. My sampling strategy, which was designed to sample the range of potential habitats will have underestimated the density of Simuliidae within charr micro-habitat and perhaps overestimated species such as Trichoptera. If this is the case then the high foraging ratio is simply due to the passive encounter rate of Simuliidae being much higher than estimated.

Despite this label of generalist, some investigations have been reported arctic charr to display prey selection. Jansen *et al.* (2002) demonstrated that when faced with the option of epbenthic large *Gammarus lacustris* or pelagic *Daphnia longispina* charr showed a preference and higher success rate preying upon *D. Longispina.* Jansen *et al.* (2002) also noted that compared to brown trout (Salmo tutta) charr were much less aggressive; a trait perhaps beneficial when they occur in higher density in winter refugia. Although they found no effect of aggression on capture success of *G. lacustris* it is plausible to imagine this may be more important when dealing with prey species which themselves are predatory or well defended such as Trichoptera or Coleoptera larvae or predatory, both having low foraging ratio's in Kårsavagge.

Rather than just a preference for the pelagic prey species, *D. Longispina* may also offer a better net energy in take for charr as they have relatively low associated costs of consumption. The same could be said of Simuliidae larvae. Although one species has been reported to repel small plecoptera by biting them (Allan *et al.*, 1987) most Simuliidae taxa have poor defensive capacities (Horne *et al.*, 1992; Malmqvist, 1994; Malmqvist and Sackmann, 1996). They also show a limited ability to detect predators compared to other taxa (Malmqvist and Sackmann, 1996, Donnelly and Sullivan, 1998); this and there propensity to drift rather than retreat into the substrate, make them particularly vulnerable to salmonid predation (Rader, 1997). Indeed, positive selection of Simuliidae by salmonids has been noted previously (De Crespin *et al.*, 2002, Steingrímsson and Gíslason, 2002). They are also an energetically profitable prey species as they tend to have deeper bodies and thus weigh more than Chironomidae of comparable length (Steingrímsson and Gíslason, 2002). This still does may not mean that

they are actively selected. Weber *et al.* (2010) noted that despite being attacked less frequently by yellow perch (*Perca flavescens*) than the goby (*Neogobius melanostomus*), alewife (*Alosa pseudoharengus*) appeared to be selected because they had a much greater capture success, the same may be true of Simuliidae larvae in Kårsavagge.

The ontogenetic diet shifts known to occur in many fish, charr included (Sandlund *et al.*, 1992; L'abee-Lund *et al.*, 1993; Steingrímsson and Gíslason, 2002; Klemetsen *et al.*, 2003; Amundsen *et al.*, 2008; Eloranta *et al.*, 2010) may also play a role in explaining observed foraging ratios. Amundsen *et al.* (2008) reported two morphs of arctic charr occurring sympatrically in Fjellfrøsvatn, a lake in northern Norway, a smaller profundal (P) morph and a larger littoral morph (L). The L-morph displayed ontogenetic diet shifts with younger, smaller (~75-150 mm in length) individuals relying much more on zooplankton, *Eurycercus lamellatus* and Chironomidae larvae than the older, larger fish whose diet consisted to a greater degree on zoobenthos and surface insects. Ontogeny was not observed in the P-morph. The size range of arctic charr from Kårsavagge puts them somewhere in between the two morphs from Fjellfrøsvatn, however a shift in diet similar to that seen in the L-morph was observed. Chironomidae were clearly the most important food source for smaller individuals as would be expected in a stream environment with no zoo plankton to speak off. As size increased a larger proportion of diet was made up by adult diptera. Given the smaller size of the fish, perhaps ontogeny within Kårsavagge is less extreme than in Fjellfrøsvatn, reflecting diets broadening rather than prey switching with age. This would make sense given the data, as despite larger fish being included, foraging ratios still suggest that Chironomidae were taken as often as they were encountered rather than actively selected or ignored. It is however difficult is

hard to determine conclusively given their overwhelming predominance in both benthic and gut samples. Perhaps if a greater number of larger fish had been captured a greater diet shift would have been observed.

Habitat complexity can play a significant role in the extent to which more profitable prey species are actively selected (Weber *et al.*, 2010). In simple habitats predators both have more information regarding potential encounter rates and greater chance of capture success, so can actively pursue the more profitable prey. If however all prey offer limited catch success and are infrequently encountered no preference is observed. The East braid displayed a complex habitat with plenty of refugia at different scales suggesting that charr are more likely to at least try and consume any prey species they come across.

A last point of note, Beatidae mayflies have been indentified from channels up stream of the East braid and given the warm water habitat it is surprising that they were not recorded in either gut or benthic samples. Rader (1997) identifies this family as particularly vulnerable to salmonid predation, so it is possible that the resident charr restrict *beatis spp* distribution through strong predation pressure.

8.5 Conclusions

8.5. i) **Arctic charr of Kårsavagge**

The landlocked Arctic charr population within the Kårsavagge probably consists of at least two morphotypes. One of these, the subject of this investigation displays rapid

maturation (as indexed by scale samples), small size, utilisation of stream rather than laucustrine habitat in the summer and a diet dominated by small Diptera larvae and adult Diptera.

8.5. ii) **Implications with regard to climate change**

It is clear that the variability of morphological and life history responses in Arctic charr make it ideally suited to life in the Arctic. Small, isolated populations are at high risk of extinction from random events and inter-annual variability. Resource polymorphism, without significant reproductive isolation as demonstrated by populations of Arctic charr, enhances survival by spreading the risk, as the probability that at least one morph has successful recruitment is high. It would be interesting to investigate if Arctic charr are less prone to speciation than other salmonids. This flexibility has evolved over millennia to cope with the particular environmental questions posed by the Arctic. If conditions continue to alter at their current rate the combination of increasing temperatures and pressure from migrating species may push charr to the brink of extinction.

In the short term, predicted warming may lead to a reduction in habitat of this dwarf morph, as increased glacial flows give the river more power and mobilize greater volumes of sediment. Higher glacial flows may reconnect the East and West braid, increasing turbidity and reducing the quality of the habitat. Within the lake, increased temperatures will lead to higher productively and the introduction (if it is not already present) of a planktivorous morph. Once the glacier has melted the reduction in SSC may extend the available habitat to the dwarf so long as flows are retained. However, with

increased temperatures population fitness and recruitment will be reduced. If warming continues the charr population will decrease and the top predator will eventually be lost from these streams.

Chapter 9 - Discussion and Implications

9.1 Introduction

This chapter outlines how the major themes running through this thesis feed into current theoretical frameworks governing stream structure and function. It highlights the major research findings and how these relate to the project objectives:

Obj$_1$ - Apply and evaluate the ARISE classification system longitudinally and laterally within the Kårsavagge system (Chapter 4)

Obj$_2$ - Investigate the physicochemical habitat variability longitudinally and laterally within the basin and identify the key drivers of this variability (Chapters 3, 4, 5 and 6)

Obj$_3$ – Investigate variation and biodiversity within the biotic component of the stream community and relate this to physicochemical habitat template. (Chapters 5 and 6)

Obj$_4$ – Assess the potential trajectory of the Kårsavagge system in the light of predicted climate change (Chapter 7 but also 3, 4, 5 and 6).

9.2 Key findings of the research

Local climate and topography interact in the Kårsavagge to produce a highly complex hydrological system with flows dominated by melt water. The majority of melt generated by the Kårsa glacier and surrounding snowpack's joins the bulk flow via an extensive channelized system. A proportion also infiltrates into shallow hill slope aquifers. Springs sourced from these aquifers rise where the valley floor levels out (in the upper and lower braided section) and add several distinct physico-chemical signals to those already present. This matrix of sources and routing in the upper catchment creates a range of distinct habitat patches laterally that contribute to the high beta diversity observed within the benthic macroinvertebrates and sustain a population of Arctic charr (Figure 9.1). The high benthic diversity observed laterally is at odds with the very low diversity recorded longitudinally in the upper section. Despite temperatures increasing steadily from the glacial source, above the first lake, main channel conditions retain a strong glacial influence with high suspended sediment concentrations, low Pfankuch scores, high diurnal variability and subsequently low primary productivity. This is reflected in the invertebrate stream community, K1, K2 and K4, the top three main channel sites were dominated by *Diamesa spp*. and had low richness and diversity.

The first lake, Bajimus Gorsajavri has a significant impact with respect to main channel biodiversity. Communities show a marked departure from those upstream with a significant increase in chlorophyll a concentration, Chironomidae shifting from Diamesinae to Orthocladiinae dominance and much greater contribution from non Diptera groups such as Plecoptera, Ephemeroptera and Trichoptera. Consequently benthic richness and diversity scores rise sharply, exceeding those recorded laterally within the

upper basin. This sharp differentiation between main channel communities upstream and downstream of first lake is reflected in several channel indices; though not all. Average SCC and Pfankuch bed index drop significantly and there is a reduction in the amplitude of diurnal cycling of both flow and temperature. The lack of a sharp increase in absolute water temperatures, which continue to rise at a rate similar to that over the preceding longitudinal profile, suggests that the major impact of the first lake, and indeed the major barriers to macro benthic distribution relate to stability and SCC rather than temperature.

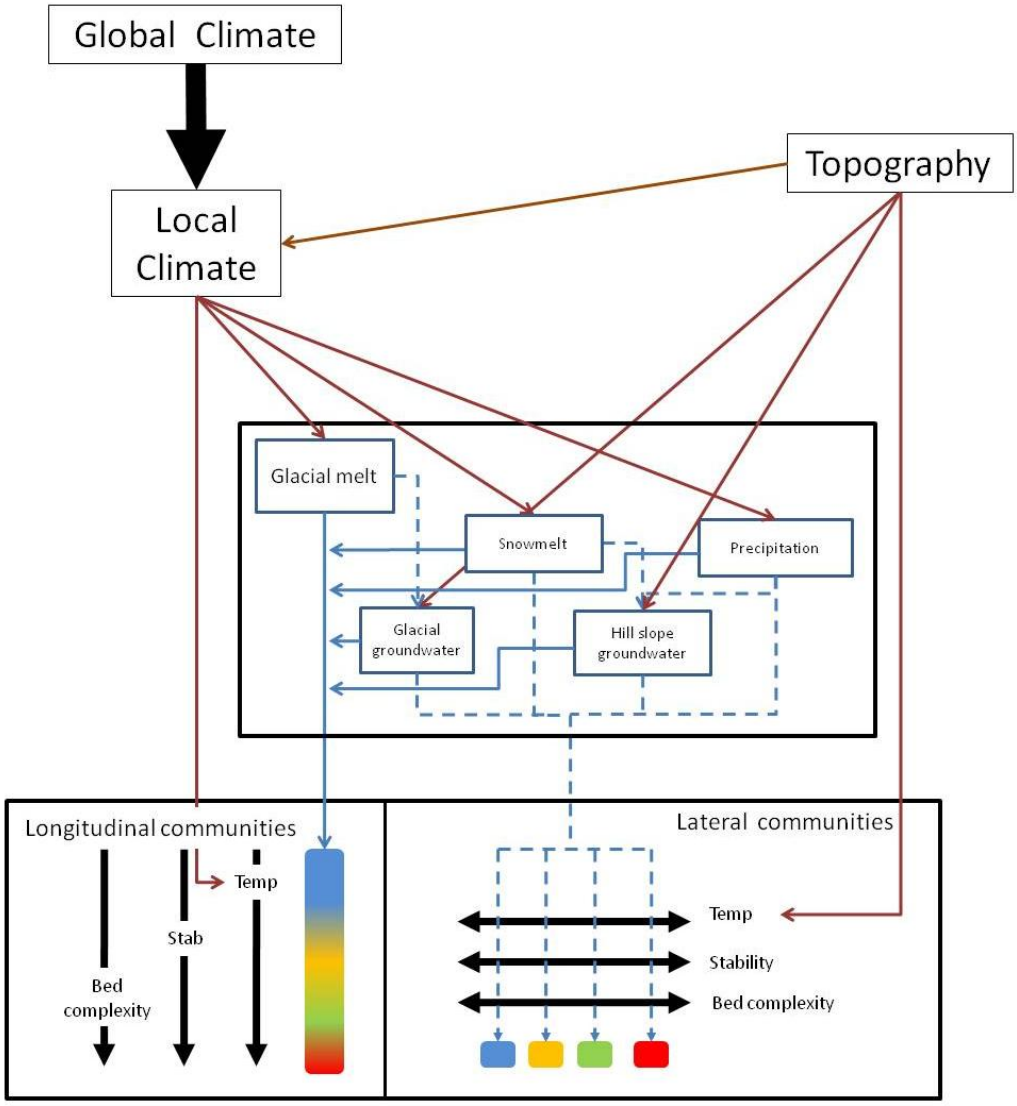

Figure 9.1 - Conceptual model of how global and local climatological variables interact dynamically with a variety of water sources to produce the high degree of lateral habitat (and therefore biological) diversity within Kårsavagge.

9.3 Water temperature

Water temperature has been suggested as a Key habitat variable, both in terms of directly limiting species distribution and as an indirect identifier of dominant water source (Ward, 1994; Füreder *et al.*, 2001; Milner *et al.*, 2001a; Brown *et al.*, 2003). It is therefore closely related to both objectives one and two. This chapter analyses the extent of spatial and temporal thermal variability within the surface waters of the Kårsavagge relating it to proposed water sources, forcing hydroclimatological variables and position in the longitudinal profile. Melt water dominance was illustrated as discharge at all gauged sites was strongly correlated with air temperatures. Safety precluded measurements during peak meltwater generation in spring but over the two summer field seasons peaks in discharge were associated with precipitation events.

The accepted pattern of longitudinal departure from source temperature driven by atmospheric forcing (Irons and Oswood, 1992a) and tributary inputs (Uehlinger *et al.*, 2003) with lakes acting as serial discontinuities (Ward and Stanford, 1983a) was generally up held in the Kårsavagge. Water column temperatures in the main channel increased longitudinally from the glacial source with the rate of increase dependent upon the reach type. The most rapid thermal increase occurred between K1 and K2, a region where the channel braids and additional flow from rhithral and groundwater tributaries is added (containing sites B1-B16). Braided confluence zones provide a nick point in the general longitudinal thermal profile as they combine both increased potential for atmospheric forcing and warmer water inputs.

The longitudinal thermal patterns within the Kårsa River illustrate a combination of the River continuum concept (Vannote *et al.*, 1980) and the stream zonation concept (Illies and Botosaneanu, 1963) as the gentle gradient of rising temperatures is interrupted by zones where tributary inputs and geomorphology interact to produce regions of rapid increase. Diurnal cycling was present at all sites during the summer however these cycles were buffered at K1 by the proximity of the Kårsa glacier and below both lakes. This thermal buffering ties in neatly with the serial discontinuity concept (Ward and Stanford, 1983; Stanford and Ward, 2001) though the downstream extent of each stores impact on thermal variability is store dependent.

The investigation into lateral patterns in the upper braided section revealed the high degree of lateral thermal variation within this system. Average temperatures across the upper braids ranged from 2.77°C to 8.76°C over 0.3km. This variability was maintained by differences in water source and channel aspect with south facing snowmelt channels having the highest degree of thermal variability. In general thermal patterns in channels followed predictions of Ward (1994), and latterly by Brown (Brown *et al.*, 2003; Brown and Hannah, 2008). Although aspect has been highlighted as a key determinant of temperature in many terrestrial studies its impact on streams is has rarely been reported (but see Hannah and Brown, 2008). In small, high latitude, strongly East-West orientated systems there is potential for intense solar heating during the summer. Thermal patterns within the North facing snowmelt stream were closer to those within some glacial channels in the braids than they were to the South facing snowmelt stream. The extent of this lateral thermal variability in comparison to that observed longitudinally is used to highlight the importance of the lateral component with regards to thermal habitat.

The hyporhiec corridor concept (Stanford and Ward, 1993) emphasizes the importance of alluvial flood plains in promoting vertical and lateral connectivity within river systems and although focused on much larger rivers it describes well the habitat heterogeneity observed within the upper braided section, where numerous water sources interact. Braided floodplains such as those in the Kårsavagge contain numerous ecotones, in this chapter thermal transitions have been emphasized, but the habitat heterogeneity provided by these mixing waters created relative biodiversity hotspots (Gray *et al.*, 2006). In subsequent chapters this habitat diversity was investigated further and related to macroinvertebrate and fish distribution to address objectives two and three more completely.

9.4 Water chemistry

This chapter investigated chemistry of surface waters within the Kårsavagge to build upon work in chapter three to try and elucidate the sources of the high degree of lateral thermal variability. It is focused on objective one and attempts to apply the ARISE model (Brown *et al.*, 2003; 2009), first tested in an alpine environment with distinct water routing, to the larger and less well defined streams within the Kårsavagge. The ARISE model uses the percentage flow from different water sources to categorize stream types.

As reported in Chapter 5, all of the highest flows recorded within the summer were associated with precipitation events. Stable isotope analysis showed that despite this, snow and ice melt provides the bulk of summer flow. The dominance of these cryospheric water sources within the Kårsavagge will wane with climate change as

warmer temperatures reduce glacier mass balance and snowfall. A transition from the current scenario to one dominated by precipitation will result in a flashy, more disturbed regime as observed on those days of heavy rainfall.

In contrast with the thermal regime, variation in water chemistry laterally exceeded that longitudinally. Three key water 'types' drop out of the analysis via solute concentrations: i) very dilute postulated quick-flow ii) waters with high solute concentration, particularly sulphate (SO_4^{2-}), postulated glacial sourced distributed flow and iii) waters with high solute concentrations, particularly silicate (Si), but lower sulphate, postulated hill slope groundwater. These values, along with snow samples were used to define end members for use in the ARISE mixing model.

The ARISE model successfully separated out proportions of water sources longitudinally along the main channel, illustrating the dominance of meltwater in the upper catchment with distributed flow and quick-flow making up the majority of flows at the top three sampling sites over both years. The seasonal evolution of flow path within the upper Kårsavagge follows the model put forwarded by Smith *et al.*, (2001), as the distributed system gradually becomes more dominant over the summer. However within Kårsa the model does not move towards the final groundwater dominated phase. This is a potential departure from the summer hydrologic pattern recorded previously in alpine environments (e.g. Malard *et al.*, 1999; Brown *et al.*, 2006c). The lack of variability in the lower sites may suggest a limitation in the ARISE model to adequately represent shifts in water sources within such a large catchment where sources of chemical species vary spatially.

Small scale variability in postulated water source within the braided section links into the rapid temperature acquisition in this section noted in Chapter 4. This thermal increase would appear to be related, at least in part to interaction with ground water springs as samples from the main channel at the end of the braids show a shift towards the groundwater end member with respect to the samples at the start. This mixing of spring and main channel sources fits into the idea of vertical-lateral connectivity hypothesis of Stanford and Ward (1993) where of surface-hyporhiec contact provide densely packed ecotones and high habitat heterogeneity.

9.5 Macroinvertebrate distribution

Chapters 5 and 6 attempted to categorize some of the longitudinal and lateral physico-chemical variability relating to the first two project objectives. Chapters 6 and 7 relate to objective three, investigating the extent to which this variation was reflected in the distribution of aquatic species. Chapter 7 deals with the distribution of a population of Arctic char whilst chapter 6 focuses on the benthic macroinvertebrate community.

The strong longitudinal zonation of macroinvertebrates in the Kårsavagge corresponds to the model proposed by Milner *et al.*, (2001a) with colder, more unstable sites close to the glacial source dominated by *Diamesa spp*. This model also notes the potential impact of lakes as habitat modifiers and within Kårsa the first lake appears to be the key factor structuring the macroinvertebrate community. Macroinvertebrate communities in the Milner *et al.*, (2001a) model are primarily described by T^{max}, although the impact of bed stability is alluded to. Since this model was proposed, several investigations have

observed bed stability limits macro benthos to kryal-type communities despite high T^{max} (Snook and Milner, 2001; Gíslason *et al.*, 2000). T^{max} longitudinally in the Kårsa rose rapidly, but a kryal-type community dominated until the top lake. The key habitat impact of this lake was to reduce the strong glacial signal with reduced SCC, reduced Pfankuch bed index score and reduced thermal variability. The dominant role of the lake as a habitat modifier in this system is consistent with the serial discontinuity concept (Stanford and Ward, 2001). However there is no gradual recovery from to the pre-lake conditions, the reduction of in glacial influence represents a permanent shift. The sharp delineation between macroinvertebrate communities from sites with a strong glacial signal and those without has major implications regarding system response to predicated climate change (Figure 9.2). Within this system glacial signal rather than thermal conditions maintain the kryal type community. This may mean that rather than a gradual shift in main channel community composition the current species make up will be retained until a tipping point corresponding to a minimum glacial influence is reached. Past this minimum there will be a rapid colonization of the headwater sections by species common downstream (and in lateral channels). When this tipping point is reached depends on how the recession of the Kårsa glacier impacts SSC and stream stability.

The phyiscochemical variability observed laterally, and highlighted in earlier chapters was reflected in the benthic macroinvertebrate community. Cluster analysis incorporating all of the 2009 macro invertebrate samples identified several communities within the upper braids as more similar to those downstream of the lake than they were to proximate channels. The potential for this lateral dimension to influence and add to the ecological functioning of main stream channels has been highlighted in several theoretical models:

the flood pulse concept (Junk *et al.*, 1989), the four dimensional model of lotic systems (Ward, 1989), the expanded serial discontinuity concept (Ward and Stanford, 1995) and to a lesser degree the Telescoping ecosystem model (Fisher *et al.*, 1998). However, despite its 'intrinsic value for local biodiversity' forming the mainstay of many temperate ecological management and restoration projects (e.g. Tockner *et al.*, 1998; Brunke *et al.*, 2003; Woolsey *et al.*, 2007), in Arctic and Alpine systems this lateral component has only recently been incorporated (Arscott *et al.*, 2005; Gray and Harding, 2009; Burgherr *et al.*, 2002).

The results presented in this chapter highlight the need for extending the sphere of Arctic and Alpine research laterally, especially in regions such as the upper braids where several different water types coalesce. Beta diversity between channels within this upper plateau was equivalent to that observed along the entire longitudinal sampling profile and similar findings have been made in the Val Roseg catchment in Switzerland (Burgherr *et al.*, 2002). In both regions, biotic diversity is driven by a complex range of habitats and these in turn are formed by the interaction of contrasting water sources and a strong disturbance regime over time. Identification of these local of biodiversity hotspots and a greater awareness of what drives the communities within them is vital as we move into a world of predicted climate change. These oases of diversity will play a major role in shaping the trajectory of arctic and alpine lotic communities into the future as the water source variation that creates them evolves (See Figure 9.2)

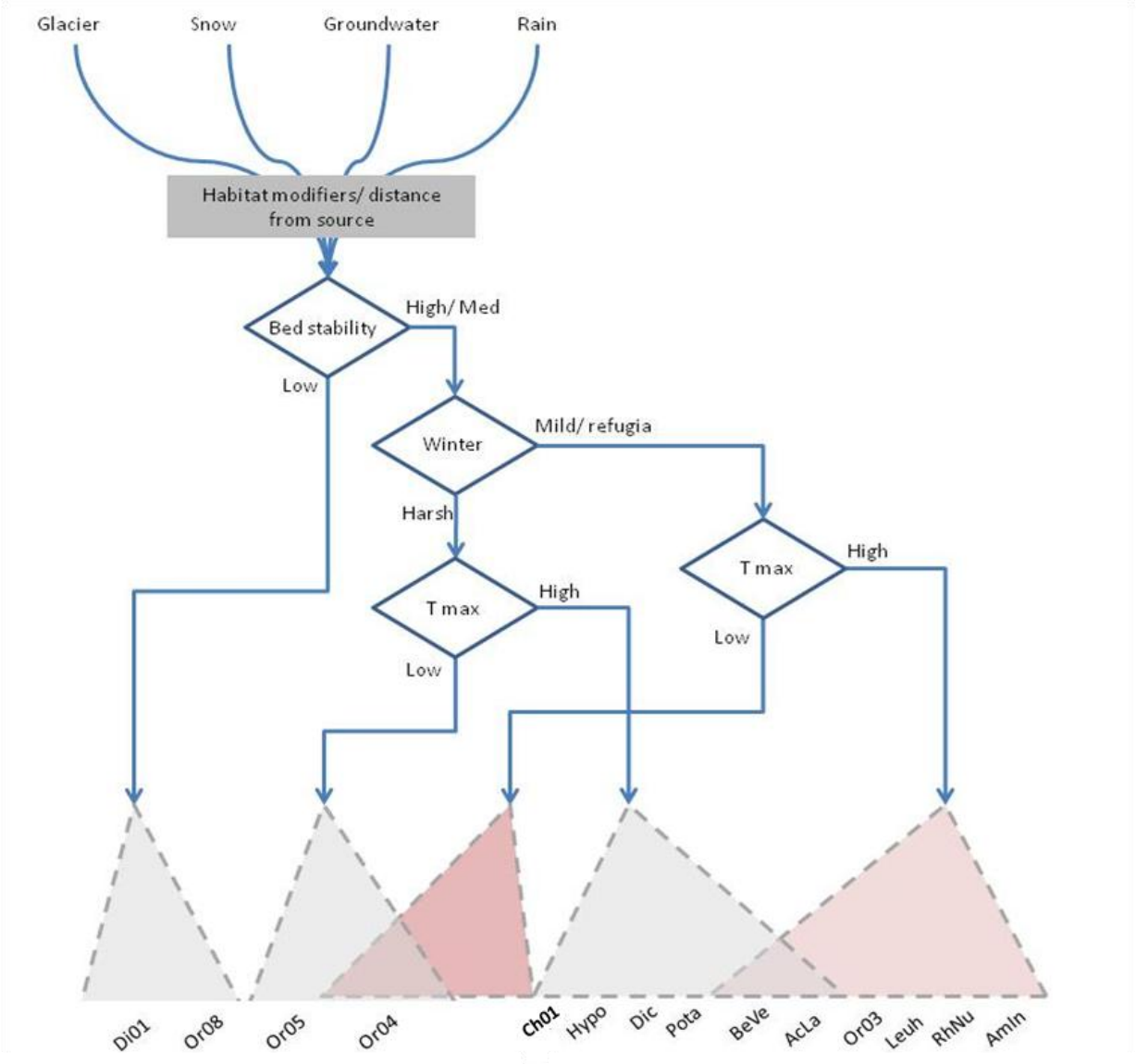

Figure 9.2 - Conceptual model illustrating key habitat filters acting within Kårsavagge that determine whether a species is found at a particular site. Taxa codes: Di01 (*Diamesa spp.*), Or08 (*Paratrissocladius spp.*), Or05 (*Orthocladius spp.*), Or04 (*Cricotopus spp.*), Ch01 (*Micropsectra spp.*), Hypo (Hydroporinae), Dic (Dicranata sp.), Pota (*Potamophylax spp.*), BeVe (*Baetis vernus var.*), AcLa (*Acentrella lapponica*), Or03 (*Chaetocladius spp.*), Leuh (*Leuctra hippopus*), RhNu (*Rhyacophila nubile*), AmIn (*Ameletus inapinatus*).

9.6 Arctic charr

The range and scope of benthic diversity recorded in chapter 7, and the habitat variability described in previous chapters illustrates the complexity of Arctic catchments. Chapter 8 adds another layer to this complexity by presenting a detailed investigation of a previously unstudied population of Arctic char found within the lower braids above the first lake. All char recorded from Kårsa conform to the dwarf morphotype observed in similar environments around the Arctic (Jonsson *et al.*, 1988; Gullestad and Klemetsen, 1997; Jonsson and Jonsson, 2001). Fork length of captured fish ranged from 35 to 194mm, displayed a unimodal distribution with a maximum age estimated to be around 5yrs. The dwarf morph matures faster and does not exhibit the diadromous behavior of the larger body morphs (Gullestad and Klemetsen, 1997; Klemetsen *et al.*, 2003a). Anecdotal evidence from regular walkers and fishermen suggests that another, larger morph exists within the system and given the size and nature of the lake-stream network this would seem highly likely (Riget *et al.*, 2000) however the extent to which different morphs exist was beyond the realm of this study. The range of ages and maturity observed within the sampled dwarf fish suggests that they may represent a landlocked, relict population. A spatially and temporally more extensive investigation would be required to elucidate to what extent this is actually the case.

This investigation was restricted to the braided section just above Bajimus Gorsajavri and detailed electro fishing was only possible within the smaller channels. Despite this limited extent it was possible to identify key habitats with regards to charr density. Over both field seasons no charr were observed in any channel with a direct glacial influence. It is suspected that this is due to high loads of suspended sediment within these channels. High SSC has been shown to increase stress and physically damage salmonid fish (Lake and Hinch, 1999; Bilotta

and Brazier, 2008) and the high associated turbidity restricts catch efficiency of visual predators (Berg and Northcote, 1985; Korstrom and Birtwell, 2006). In contrast high charr density tended to be associated with pools/ undercut banks within groundwater fed channels. Lake dwelling charr migrate between habitats to maximize productivity (Babaluk *et al.*, 2001; Svenning and Gullestad, 2002; Witkowski *et al.*, 2008) and it is probable that productivity of forage grounds within the braided streams exceeds that of the lake. What was witnessed during this short sample season probably reflected a range expansion into more profitable habitat, and within this utilization of the most profitable patches with respect to hydraulic factors (Guensch *et al.*, 2001).

An attempt was made to differentiate between the diets of fish in different size classes with a view to informing population hierarchy. Many salmonid fish (including Charr) set up dominance hierarchies which strongly influence the quality of habitat they utilize (Nakano, 1995; Gilmour *et al.*, 2005). Results of diet analysis show a discrepancy between the gut contents of smaller and larger individuals, with samples from larger fish containing a significantly higher proportion of adult Diptera (Figure 8.8). Despite this clear difference, the range of foraging techniques employed by Arctic charr means the extent to which this difference is related to dominance behavior, unrelated habitat utilization or gape limitation is unclear.

Hydrogeomorphic barriers in the form of several large waterfalls and the high turbidity of the main channel limit the range of Arctic charr in the upper Kårsavagge. This restricted range may play an important role in the distribution of invertebrates. Baetidae, very common in channels within the upper braided section were rarely encountered in channels containing charr, despite these channels displaying similar physicochemical regimes. This structure may

be an artifact of my data rather than any real difference; however top down control of invertebrates by fish predators has been illustrated and used as a management technique for over a century (Howard *et al.*, 2007). The low productivity of the Arctic increases top down pressure and thus there is strong evolutionary pressure to be able identify and avoid this threat. As species ranges shift over the next 100 years; direct and indirect control of prey by predators will play an important role in determining how communities are structured.

9.7 The habitat templet of Kårsavagge

The data from chapters 7 and 8 illustrate how the biotic community maps onto the different habitat templates present within Kårsavagge. The physicochemical habitat templet (Poff and Ward, 1990; Poff *et al.*, 1996) is defined by a combination of filters acting at different spatial and temporal scales or 'levels'. Kårsavagge can be seen as a nested hierarchy of systems, with changes in one cascading down to influence the structure and function of those subordinate to it (Frissell *et al.*, 1986; Hildrew and Townsend, 1994; Hieber *et al.*, 2005). Each of these nested systems presents filters through which taxa must pass if they are to persist, right down to specific micro-habitat envelopes or patches (Huryn, 2005; Heino *et al.*, 2007). It must be noted that persistence at one level does not mean a taxa is ubiquitous within all its nested sublevels, simply that at any given time a population is present in one or more microhabitats (Begon *et al.*, 2002).

Currently, the dominant filter operating at the catchment scale in Kårsavagge and all arctic habitats is the extreme seasonality of the climate (Danks *et al.*, 1994; Olsson *et al.*, 2003; Danks, 2004; Huryn, 2005; Füreder, 2007; Milner *et al.*, 2009). All organisms persisting have

traits equipping them to cope when flows cease and temperatures fall (Strathdee and Bale, 1998; Danks, 2004; 2007; Winterbourn *et al.*, 2008; Lencioni *et al.*, 2009). In terms of the habitat template, the arctic winter would be classed as a high magnitude, predictable, long term pulse event (Townsend and Hildrew, 1994; Lake, 2000). This is only from the perspective of those species for which the summer provides preferential conditions; given the hydro-period for some sites (e.g. K1) it could be argued that the melt season is the disturbance event (see Uehlinger *et al.*, 2010). Townsend and Hildrew (1994) suggest that the more predictable a disturbance the lower its impact, as taxa evolve to adaptively avoid or mitigate impacts. Hence even taxa that are not freeze tolerant can persist through behavioural adaptation such as utilizing refugia or an evolved resistant life stage (i.e. *Aeides nigripes* eggs) (Danks *et al.*, 1994; Danks, 2007). The former is only needed if generation time is long enough to encompass the winter, which for multi- or univoltine species such as *Diamesa incallida* (Walker) it is not (Nolte and Hoffmann, 1992).However semi-voltinism is common in arctic taxa due to the low productivity and cool temperatures (Strathdee and Bale, 1998; Danks, 2004; Finn and Poff, 2005) species that are not freeze tolerant will only fit through a habitat filter which provides appropriate refugia. If no winter refugia are present then there will either be no individuals or an ephemeral sink population, maintained through oviposition by adults dispersing from permanent populations elsewhere.

In some Alpine streams, with significant groundwater input, benthic conditions ameliorate as winter sets in (Battin *et al.*, 2004; Uehlinger *et al.*, 2010). The cessation of glacial melt reduces SSC and inputs of near freezing water. This provides a window of high productivity in flows dominated by groundwater and in these systems resting stages may be required to mitigate the impact of spring and summer flows. In Kårsavagge, and other arctic systems

windows of productivity are limited by winter insolation and the lack of groundwater input (ACIA, 2004).

As there are hierarchies of spatial scales, so there are hierarchies of temporal scales. The occurrence of diel flow 'events' in arctic and alpine streams is well documented (e.g. (Ward, 1994; Füreder *et al.*, 2001; Arscott *et al.*, 2003; Brown *et al.*, 2003; Hieber *et al.*, 2003; Malard *et al.*, 2003; 2006; Silveri *et al.*, 2009). Diel flow events are both low in magnitude and highly predictable so have limited impact on the post event community. Rainfall events in contrast present an unpredictable disturbance. The impact of each rainfall event is dependent on its magnitude and duration, the antecedent conditions and catchment morphology (Caissie, 2006; Brown and Hannah, 2007; Cadbury *et al.*, 2008). If flows rise faster than during the diel increase or exceed normal levels (as observed at K1, K2, B1 and B12 see Figure 5.2 and 5.3) then impact may be high. In this instance habitats that are insufficiently stable or varied to provide refugia against large scale extreme impact events (such as spring melt) may y*et al*low communities to mitigate more frequent but unpredictable medium magnitude flows. This may be one factor accounting for the more extensive and diverse macroinvertebrate communities found in more stable channels within the upper braided section when compared to the highly unstable main channel.

The difference between communities sampled in the upper section of Kårsavagge is also dependant on habitat filters presented by the dominant water source. The main glacial channel is subject to high SSC, the most extreme diel flows, and constant low temperatures. These filter off all taxa which would be damaged by the scouring sediment concentrations, cold temperatures or require a high algal resource. In contrast, some channels in the upper braided section attain temperatures above 10°C due to their size and aspect. These more stable,

warmer channels support patches of moss (increasing benthic habitat complexity (Bowden *et al.*, 1994; Suren, 1991) and algal production is liable to be relatively high. The filters presented by these channels result in a wider variety of traits, including generalists when compared to the specialists of the glacial stem.

Another filter presented by the upper braided section is its isolation. It is separated from the lower sections of stream by several waterfalls. This filters out arctic charr, which could persist in the warmer, clearer, snowmelt and groundwater fed channels of the upper braids during the summer months as they do in the lower braids, but cannot overcome the hydrogeomorphic barrier which separates the two.

The patchy habitat template of Kårsavagge has produced a variety of communites with each with a dominant suite of traits. Communities along the main glacial stem above the lakes (K1, K4 and K3) are dominated by highly specialised cold stenothermal taxa resistant to disturbance. Those in the upper braided section (B1-B16) are dominated by more generalist, eurythermal taxa with short generation times, resting stages or effective dispersive adult phases. The lower braided section is dominated by a similar raft of taxa as occur in the upper braids but the increased connectivity to the lower catchment negates an airborne dispersive phase allowing arctic charr to utilize the habitat. Traits below the first lake tend towards behavioural freeze avoidance, multi-voltine life cycles, eurythermal tolerance and specialism's relating to acquisition of a widening resource base.

9.8 The Kårsavagge and climate change

Predicted increases in Arctic air temperatures over the coming decades will have significant impacts on the type and distribution of physicochemical habitat patches within the Kårsavagge. As illustrated above and in previous chapters it is this variation in habitat patches both longitudinally and laterally which drives biodiversity within the system. Any change in the relative proportions of habitat will have consequences for local and regional biodiversity.

Milner *et al.* (2009) highlight the plight of glacial sourced rivers in Arctic and Alpine environments as the specter of global warming looms large. Warming in the Arctic is predicted to be greater than at any time during recent history (ACIA, 2004; IPCC, 2007a) and if this is the case responsive systems such as the Kårsavagge will elicit rapid shifts in water source dominance. Snout measurements over the past century illustrate the rate with which the Kara glacier responds to increasing temperatures (Boding, 1991) and it has been suggested that the glacier is likely have disappeared within the next 70 years (Plant, 2009). In this system it is the strong glacial influence that drives much of the current invertebrate and fish distribution within the valley. Warming will have both short and long term consequences. In the short term, increased melt will provide higher glacial flows that may mobilize larger volumes of sediment leading to a much stronger glacial signal within the main channel. With regards to distribution of biota the extent of the impact will depend on channel migration. If channel evolution proceeds in such a way as to increase the glacial influence upon rhithral or krenal channels within either braided section then these communities will disappear and diversity within the headwaters will reduce. This scenario would have particular pertinence for the population of Arctic charr, which, if restricted to the lake may struggle to maintain a viable population.

If channel evolution does not act to homogenize physicochemistry within the braided sections then the impact of global warming on biodiversity, at least above the first lake in the short term will be limited as the seasonal disturbance regime rather than temperature per se limits the biotic community. Increased temperatures will elevate local productivity and standing crops although the extent to which these can increase is will be limited by the availability of nutrients. To this end the impact of increased terrestrial productivity will be important. Allochthonous inputs could be utilized at higher temperatures, releasing nutrients and expanding the range of invertebrate guilds present within the upper catchment. Increasing temperatures will have negative impacts upon the charr with their preference for very low thermal conditions (Larsson, 2005).

Below the first lake, where the glacial signal is reduced, warming will increase productivity and perhaps enable colonization of warmer water species. The key short term shift may be in the predominance of different guilds. At present it appears that Bajimus Gorsajavri acts as a sink for both nutrients and matter, providing limited suspended particulates to the downstream system; as evidenced by the low numbers of filter feeders at K6. In regions where lakes act as sources rather than sinks guilds in the outflows tend to be dominated by filter feeders (Richardson and Mackay, 1991; Donath and Robinson, 2001). With increasing temperatures and the potential of increasing mineral input from the glacier it may be that productivity in the top lake increases, shifting communities in the outlet regions from Chironomidae to Simuliidae dominance.

In the long term, total disappearance of the Kårsa glacier will presumably have dramatic impacts on hydrological and ecological functioning of the valley system. The remaining hydrological regime will depend upon how the climate develops. Current models predict a

shift to warmer wetter conditions with the greatest relative increases in both temperature and precipitation to occur in winter (ACIA, 2004; IPCC, 2007b). So far winter warming at Abisko has led to an increase in winter snow accumulation at ANS but this is unlikely to continue indefinitely (Kohler *et al.,* 2008). In the long term warming will reduce snow accumulation and shorten the snow cover season (ACIA, 2004; IPCC, 2007b; Kohler *et al.*, 2008). This shift in the absolute and relative inputs from cryospheric sources and rainfall into the system will have a marked impact on hydrological functioning. Reduced longevity of rhithral inputs in combination with changes in how and when groundwater recharge occurs may lead to many of the channels, especially towards the valley head becoming ephemeral.

The impact of these long term hydrological changes on the biota is difficult to predict as they will interact with and feedback to other, concomitantly evolving landscape components. It is likely that by 2100 stream ecologists sampling within the Kårsavagge will record a community dominated by different species than those recorded in 2009. Once the glacier is gone, the glacial signal that appears to give the lake such significance will be removed and a homogenization of non-outlet communities upstream/ downstream of the lake may occur (Figure 9.3). As the range of water sources reduces, lateral diversity will also reduce, though again this may in part be mediated by variability imposed by other factors such as the distribution of terrestrial vegetation.

Winters are becoming shorter as spring snowmelt happens earlier and autumn freeze up occurs later (ACIA, 2004). Currently the alpine pattern of gradually increasing groundwater contribution to flow over the melt season as suggested by Smith *et al.*, (2001) is not repeated within the upper section of Kårsavagge. However if the melt season continues to elongate as

predicated (ACIA, 2004; IPCC, 2007a) there is more chance of seasonal snowpack's becoming exhausted with flows then having greater reliance on groundwater inputs.

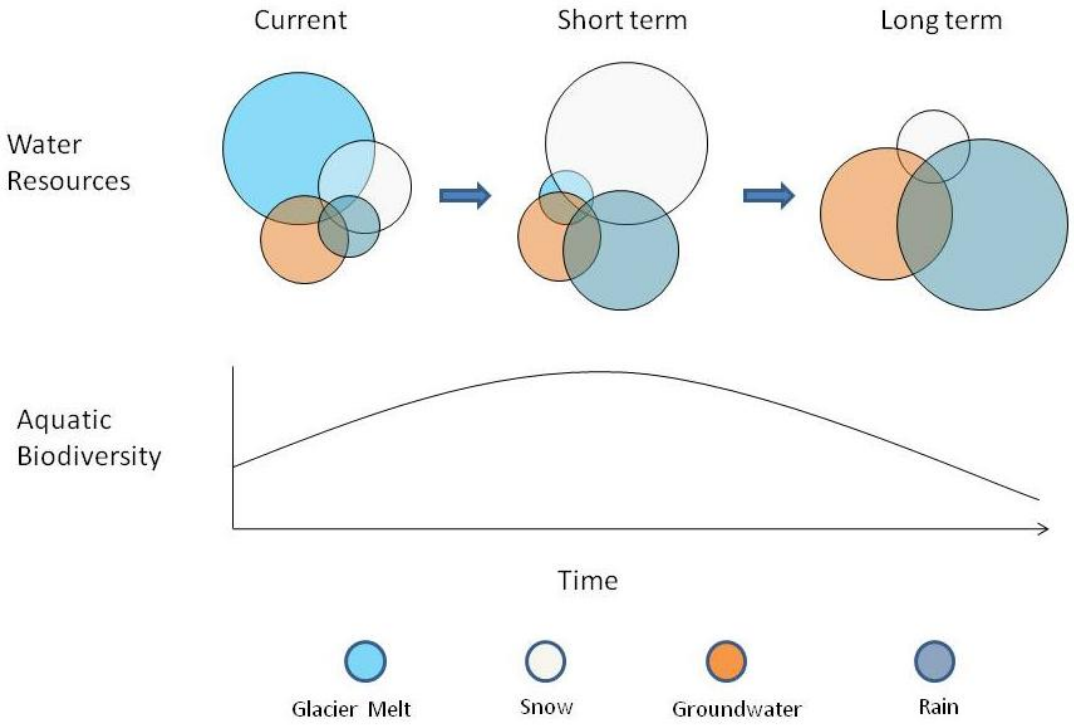

Figure 9.3 - Conceptual model illustrating the potential trajectory of biodiversity within Kårsavagge and other similar glacierized basins in response to shifts in water source dominance as a result of climate change.

As air temperatures increase and input from cryospheric sources fall, average water temperatures will steadily rise. Despite the reduction in glacial signal this rise in temperature will have a negative impact on the Arctic charr population of the lower braids. Productivity within the system will increase but as the optimum temperature for charr growth is consistently exceeded the population will be at ever greater risk from competitors (Helland *et al.*, 2011; Urban *et al.*, 2011). However the isolated nature of this population, with poor

linkage to other water bodies (large waterfalls) makes natural replacement by other salmonid species with greater thermal tolerance less likely. As long as charr remain the sole fish species and temperatures do not prohibit breading a population will be retained though stress related impacts will reduce their predation impact. If temperatures rise further a shift in community composition may occur, with predatory macroinvertebrates such as Plecoptera replacing charr as dominant predators or unpredictable trophic cascades ensuing (Kishi *et al.*, 2005).

9.9 Recommendations for future work

Future work to extent the findings of this project should focus on aspects related to how the system will develop as the climate warms. This project identified the impact lateral water source variability has on local biodiversity within an Arctic stream systems. The implication is that many systems may be more diverse than at first thought and as a result sources of colonists for main channels with ameliorating conditions may be close at hand. Lateral diversity within Arctic systems need to be quantified and taken into account in future modeling scenarios relating to species distributions. A comparison between main channel communities to the total lateral community would provide an ideal way of monitoring system development, the more similar the further down the road of climatic development a system is.

The discovery of a relict population of Arctic charr was a major finding of the project. The future development of this population and others like it depends on how they utilize the habitat. Radio tagging of salmonids has proved successful in the past (e.g. Horká *et al.*, 2010) and a gate installed at the mouth of the main groundwater channel would show which fish migrated into the channel and when.

The main determinant of longitudinal invertebrate community was the first lake. The transformative impact of this lake on community development appeared to be related to a damping of the overall glacial signal rather than any thermal impact. However, despite the lack of glacial signal lateral communities above the lake did not resemble main channel communities below it. The suspicion is that lateral communities above the lake were limited by freezing winter conditions, though any large scale geomorphic disturbances caused during initial snowmelt may also be a factor. Overwinter thermal monitoring, in combination with a logger which recorded kinetic movement would identify which if either of these issues were present within lateral channels and thus identify reasons for this lateral/ longitudinal difference.

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Appendix A

Species list, taxa codes and total numbers of individuals encountered at longitudinal sites. Data for both 2008 (08) and 2009 (09) are presented. " **-** " = no individuals recorded; na = 2008 Chironomidae data not identified to family.

Taxa	**Code**	**Sites**											
		K1		**K2**		**K4**		**K6**		**K8**		**K9**	
		08	09	08	09	08	09	08	09	08	09	08	09
Diptera													
Simuliidae	Sim	-	-	**4**	-	**1**	-	**106**	**28**	**321**	**12**	**9**	**5**
Chironomidae	Chr	**108**	**128**	**1431**	**952**	**807**	**904**	**1368**	**874**	**95**	**91**	**116**	**138**
Diamesa spp.	Di01	na	**122**	na	**745**	na	**785**	na	**5**	na	**1**	na	-
Potthastia spp.	Di02	na	-	na	-	na	-	na	-	na	-	na	**4**
Pseudodiamesa spp.	Di03	na	-	na	-	na	-	na	-	na	-	na	**1**
Pseudokiefferiella spp.	Di04	na	-	na	-	na	-	na	-	na	-	na	-
Micropsectra spp.	Ch01	na	-	na	-	na	**1**	na	**55**	na	**5**	na	**26**
Paratanytarsus spp.	Ch02	na	-	na	-	na	-	na	**14**	na	-	na	-
Heterotissocladius spp.	Or01	na	-	na	**3**	na	-	na	**25**	na	**8**	na	**5**
Corynoneura spp.	Or02	na	-	na	-	na	-	na	**24**	na	-	na	**13**
Chaetocladius spp.	Or03	na	-	na	**2**	na	-	na	-	na	**34**	na	**42**
Cricotopus spp.	Or04	na	-	na	**53**	na	**29**	na	**196**	na	**1**	na	**18**
Orthocladius spp.	Or05	na	-	na	**8**	na	**45**	na	**156**	na	**1**	na	**1**
Eukiefferiella spp.	Or06	na	**2**	na	**7**	na	-	na	**6**	na	**9**	na	**9**
Limnophyes spp.	Or07	na	**1**	na	**2**	na	**12**	na	**139**	na	**2**	na	**2**
Paratrissocladius spp.	Or08	na	-	na	**127**	na	**29**	na	**18**	na	-	na	**1**
Parakiefferiella spp.	Or09	na	-	na	-	na	-	na	-	na	-	na	-
Paralimnophyes spp.	Or10	na	**1**	na	-	na	-	na	-	na	-	na	-
Psectrocladius spp.	Or11	na	-	na	-	na	-	na	-	na	**1**	na	-
Mectriocnemus spp.	Or12	na	**1**	na	-	na	-	na	-	na	-	na	-
Hydrobaenus spp.	Or13	na	-	na	-	na	**2**	na	-	na	-	na	-
Krenosmitta spp.	Or14	na	-	na	-	na	-	na	-	na	-	na	**1**
Nanocladius spp.	Or15	na	-	na	-	na	-	na	-	na	-	na	-
Rheocricotopus spp.	Or16	na	**1**	na	-	na	-	na	**2-5**	na	**2**	na	-
Stilocladius spp.	Or17	na	-	na	-	na	-	na	-	na	-	na	-
Themeniella spp.	Or18	na	-	na	**5**	na	**1**	na	**4**	na	-	na	-
Synorthocladius spp.	Or19	na	-	na	-	na	-	na	-	na	-	na	**2**
Conchapelopia spp.	Ta01	na	-	na	-	na	-	na	**18**	na	**12**	na	**1**
Thienemannimyia spp.	Ta02	na	-	na	-	na	-	na	**9**	na	**15**	na	**8**
Nilotanypus spp.	Ta03	na	-	na	-	na	-	na	-	na	-	na	**4**
Tipula sp.	Tip	-	-	-	-	-	-	-	-	-	-	-	-
Clinocera sp.	Clin	-	-	-	-	-	-	-	-	-	-	-	-
Widemannia sp.	Wid	-	-	-	-	-	-	**5**	-	-	**1**	**2**	-
Sciomyzidae	Sci	-	-	-	**2**	-	-	-	**2**	-	-	-	-
Pedicia sp.	Ped	-	-	**1**	-	-	-	-	-	-	-	-	-
Rhabdomastix sp.	Rha	-	-	**1**	-	-	-	-	-	-	-	-	-
Dicranata sp.	Dic	-	-	**3**	**2**	**4**	-	**3**	**1**	**4**	**9**	**25**	**6**
Eloeophila sp.	Elo	-	-	-	-	-	-	-	-	-	-	-	-
Scleroprocta sp.	Scl	-	-	-	**2**	-	**1**	-	-	-	-	-	-
Rhypholophus sp.	Rhy	-	-	-	-	-	-	-	-	-	-	-	-
Thaumaleidae	Tha	-	-	-	-	-	-	**1**	-	-	-	-	-
Henerodromiinae	Hen	-	-	-	-	-	-	**1**	-	-	-	-	-
Plecoptera													
Leuctra hippopus (Kempny)	LeuH	-	-	-	-	-	-	**2**	**2**	**2**	**25**	**75**	**97**
Capnia spp.	Cap	-	-	-	-	-	-	**48**	**4**	**11**	**2**	**35**	**5**
Diura bicaudata (Linnaeus)	DiBi	-	-	-	-	-	-	**1-**	**6**	**11**	**5**	**2**	**4**
Arcynopteryx compacta (McLachlan)	ArcC	-	-	-	-	-	-	-	-	**1**	-	-	-
Isoperla difformis (Klapálek)	IsDi	-	-	**1**	-	-	-	**171**	**42**	**82**	**29**	**11**	**13**
Taeniopteryx nebulosa (Linnaeus)	TaNe	-	-	-	-	-	-	**20**	**2**	**2**	**1**	**2**	**12**
Brachyptera risi (Morton)	BrRi	-	-	-	-	-	-	**1**	-	**3**	-	**1**	**2**
Amphinemura sulcicollis (Stephens)	AmSu	-	-	**2**	-	-	-	**5**	**16**	**1**	-	**5**	**5**
Protonemura meyeri (Pictet)	PrMe	-	-	-	-	-	-	-	-	-	-	**2**	**10**
Ephemeroptera													
Baetis buceratus (Eaton)	BeBc	-	-	-	**1**	-	-	**6**	-	**1**	-	-	-

Appendix A

Baetis bundyae (Lehmkuhl)	BeBn	-	**1**	**1**	-	**1**	-	**63**	**50**	**1**	**5**	**4**	**1**
Baetis vernus var.	BeVe	-	-	**1-**	**1**	**3**	**1**	**21**	**5**	**1-**	**49**	**34**	**21**
Baetis rhodani (Pictet)	BaRh	-	-	-	-	-	-	**1**	**6**	-	-	**1**	**64**
Acentrella lapponica (Bengtsson)	AcLa	-	-	**8**	-	**2**	-	**1**	-	**23**	**1**	**184**	**109**
Ephemerella aurivillii (Bengtsson)	EpAu	-	-	-	-	-	-	**25**	**11**	**2**	-	**7**	**12**
Ephemerella ignata (Poda)	EpIg	-	-	-	-	-	-	**1**	-	-	-	-	-
Paraleptophlebia submarginata (Stephens)	PaSu	-	-	-	-	-	-	-	-	**1**	-	-	-
Ameletus inapinatus (Eaton)	AmIn	-	-	-	-	-	-	-	-	**1**	**6**	-	-
Ameletus alpinus (Bengtsson)	AmAl	-	-	-	-	-	-	-	**2**	-	**5**	**7**	-
Heptagenia sulphurea (Müller)	HeSi	-	-	-	-	-	-	-	-	**1**	**2**	-	-
Heptagenia flava (Rostock)	HeFl	-	-	-	-	-	-	-	-	-	-	-	**3**
Trichoptera													
Rhyacophila nubila (Zetterstedt)	RhNu	-	-	-	-	-	-	**43**	**12**	**15**	**11**	**6**	**14**
Plectronemia conspersa (Curtis)	PlCo	-	-	-	-	-	-	-	-	**1**	-	**1**	-
Neureclipsis bimaculata (Linnaeus)	NeBi	-	-	-	-	-	-	-	-	**1**	-	-	**1**
Psychomyiidae	Psyc	-	-	-	-	-	-	**1**	-	-	-	-	-
Potamophylax spp.	Pota	-	-	**2**	**2**	**3**	**1**	-	-	**2**	**1**	**9**	**9**
Coleoptera													
Helophorus sp**.**	Helo	-	-	**1**	-	-	-	-	-	-	-	-	-
Ilybius sp.	Illy	-	-	-	-	-	-	-	-	-	-	-	-
Agabus sp.	Aga	-	-	-	**1**	-	-	-	-	-	-	-	-
Hydroporinae	Hypo	**1**	-	-	-	-	-	-	-	-	-	-	-
Dytiscidae sp. A	ColA	**2**	-	-	-	-	-	-	-	-	-	-	-
Hydraena sp.	Hydr	-	-	-	-	-	-	-	-	**1**	-	-	-
Dryops sp.	Drps	-	-	-	-	-	-	-	-	-	-	-	-
Elmidae	Elmi	**1**	-	-	-	-	-	-	-	**1**	-	-	-
Coleoptera sp. B	ColB	-	-	-	-	-	-	-	-	-	-	**1**	-
Ostracoda	Ostr.	-	-	-	-	-	-	**8**	**1**	**5**	-	-	**1**
Hydracarina	Hyca.	-	-	-	-	-	-	**5**	**2**	-	-	-	-
Turbellaria	Turb.	-	-	**1**	-	-	-	**1**	-	-	-	-	-
Gastropoda	Gast.	-	-	-	-	-	-	**1**	-	-	-	-	-
Collembola	Coll.	**1**	**6**	**6**	**2**	**3**	**8**	**4**	**6**	**1-**	-	**4**	**2**

Appendix B

Species list, taxa codes and total numbers of individuals encountered in the upper braided section in 2008. . " – " = no individuals recorded.

Taxa	Code	Sites in the upper braids 08						
		B1	B2	B6	B7	B8	B9	B10
Diptera								
Simuliidae	Sim	-	-	-	1	-	3	-
Chironomidae	Chr	16	14	49	34	6	20	2
Tipula sp.	Tip	-	-	-	-	-	-	-
Clinocera sp.	Clin	-	-	-	-	-	-	-
Widemannia sp.	Wid	-	-	-	-	-	-	-
Sciomyzidae	Sci	-	-	-	-	-	-	-
Pedicia sp.	Ped	-	-	-	-	-	-	-
Rhabdomastix sp.	Rha	-	-	-	-	-	-	-
Dicranata sp.	Dic	-	-	-	-	5	-	-
Eloeophila sp.	Elo	-	-	-	-	-	-	-
Scleroprocta sp.	Scl	-	-	-	-	-	-	-
Rhypholophus sp.	Rhy	-	-	-	-	-	-	-
Thaumaleidae	Tha	-	-	-	-	-	-	-
Henerodromiinae	Hen	-	-	-	-	-	-	-
Plecoptera								
Leuctra hippopus (Kempny)	LeuH	-	-	-	-	-	-	-
Capnia spp.	Cap	-	-	-	-	-	-	-
Diura bicaudata (Linnaeus)	DiBi	-	-	-	-	-	-	-
Arcynopteryx compacta (McLachlan)	ArcC	-	-	-	-	-	-	-
Isoperla difformis (Klapálek)	IsDi	-	-	-	-	-	-	-
Taeniopteryx nebulosa (Linnaeus)	TaNe	-	-	-	-	-	-	-
Brachyptera risi (Morton)	BrRi	-	-	-	-	-	-	-
Amphinemura sulcicollis (Stephens)	AmSu	-	-	-	-	1	-	5
Protonemura meyeri (Pictet)	PrMe	-	-	-	-	-	-	-
Ephemeroptera								
Baetis buceratus (Eaton)	BeBc	-	-	-	-	-	-	-
Baetis bundyae (Lehmkuhl)	BeBn	-	-	-	-	29	-	-
Baetis vernus var.	BeVe	-	-	-	2	7	2	14
Baetis rhodani (Pictet)	BaRh	-	-	-	-	-	-	-
Acentrella lapponica (Bengtsson)	AcLa	5	-	-	5	274	75	3
Ephemerella aurivillii (Bengtsson)	EpAu	-	-	-	-	-	-	-
Ephemerella ignata (Poda)	EpIg	-	-	-	-	-	-	-
Paraleptophlebia submarginata (Stephens)	PaSu	-	-	-	-	-	-	-
Ameletus inapinatus (Eaton)	AmIn	-	-	-	-	-	-	-
Ameletus alpinus (Bengtsson)		-	-	-	-	-	-	-
Heptagenia sulphurea (Müller)	HeSi	-	-	-	-	-	-	-
Heptagenia flava (Rostock)	HeFl	-	-	-	-	-	-	-
Trichoptera								
Rhyacophila nubila (Zetterstedt)	RhNu	-	-	-	-	-	-	-
Plectronemia conspersa (Curtis)	PlCo	-	-	-	-	-	-	-
Neureclipsis bimaculata (Linnaeus)	NeBi	-	-	-	-	-	-	-
Psychomyiidae	Psyc	-	-	-	-	-	-	-
Potamophylax spp.	Pota	-	-	-	-	15	4	5
Coleoptera								
Helophorus sp.	Helo	-	-	-	-	-	-	-
Ilybius sp.	Illy	-	-	-	-	-	-	2
Agabus sp.	Aga	-	-	-	-	1	-	-
Hydroporinae	Hypo	-	-	-	-	-	-	-
Dytiscidae sp. A	ColA	-	-	-	-	-	2	-
Hydraena sp.	Hydr	-	-	-	-	-	-	-
Dryops sp.	Drps	-	-	-	-	-	-	-
Elmidae	Elmi	-	-	-	-	-	-	-
Coleoptera sp. B	ColB	-	-	-	-	-	-	-
Ostracoda	Ostr.	-	-	-	-	3	-	17
Hydracarina	Hyca.	-	-	-	-	3	-	-
Turbellaria	Turb.	-	-	-	-	2	-	-
Gastropoda	Gast.	-	-	-	-	-	-	-
Collembola	Coll.	-	2	-	-	-	-	-

Appendix C

Species list, taxa codes and total numbers of individuals encountered in the upper braided section in 2008. "–" = no individuals recorded.

Taxa	Code	Sites in the upper braids 09									
		B1	B2	B6	B7	B8	B9	B10	B12	B13	B14
Diptera											
Simuliidae	Sim	-	-	-	-	-	-	-	8	-	2
Chironomidae	Chr	*83*	*32*	*162*	*60*	*21*	*25*	*14*	*573*	*232*	*771*
Diamesa spp.	Di01	83	29	149	57	16	-	7	250	-	165
Potthastia spp.	Di02	-	-	-	-	-	-	-	-	-	-
Pseudodiamesa spp.	Di03	-	-	-	2	1	-	2	4	-	1
Pseudokiefferiella spp.	Di04	-	-	-	-	-	-	-	-	-	14
Micropsectra spp.	Ch01	-	-	-	-	3	12	-	-	199	-
Paratanytarsus spp.	Ch02	-	-	-	-	-	8	-	-	5	-
Heterotissocladius spp.	Or01	-	-	1	-	-	-	1	-	-	-
Corynoneura spp.	Or02	-	-	-	-	-	-	2	-	-	-
Chaetocladius spp.	Or03	-	-	1	-	-	-	-	4	-	-
Cricotopus spp.	Or04	-	-	5	-	-	-	-	171	-	438
Orthocladius spp.	Or05	-	-	4	-	-	5	-	52	5	138
Eukiefferiella spp.	Or06	-	-	-	-	-	-	-	7	-	-
Limnophyes spp.	Or07	-	2	-	1	-	-	2	24	-	9
Paratrissocladius spp.	Or08	-	-	-	-	-	-	-	4	-	-
Parakiefferiella spp.	Or09	-	-	-	-	-	-	-	-	-	-
Paralimnophyes spp.	Or10	-	-	-	-	-	-	-	-	-	-
Psectrocladius spp.	Or11	-	-	-	-	-	-	-	-	-	-
Mectriocnemus spp.	Or12	-	-	1	-	-	-	-	-	-	-
Hydrobaenus spp.	Or13	-	-	1	-	-	-	-	2	-	-
Krenosmitta spp.	Or14	-	-	-	-	-	-	-	-	-	-
Nanocladius spp.	Or15	-	-	-	-	-	-	-	-	-	-
Rheocricotopus spp.	Or16	-	-	-	-	-	-	-	31	-	1
Stilocladius spp.	Or17	-	-	-	-	-	-	-	-	-	-
*Themeniella*spp.	Or18	-	1	-	-	1	-	-	24	-	5
Synorthocladius spp.	Or19	-	-	-	-	-	-	-	-	-	-
Conchapelopia spp.	Ta01	-	-	-	-	-	-	-	-	-	-
Thienemannimyia spp.	Ta02	-	-	-	-	-	-	-	-	-	-
Nilotanypus spp.	Ta03	-	-	-	-	-	-	-	-	23	-
Tipula sp.	Tip	-	-	-	-	-	-	-	1	-	-
Clinocera sp.	Clin	-	-	-	-	-	3	-	-	-	-
Widemannia sp.	Wid	-	-	-	-	-	-	1	-	-	-
Sciomyzidae	Sci	-	-	-	-	-	-	-	-	-	-
Pedicia sp.	Ped	-	-	-	-	-	-	-	2	-	-
Rhabdomastix sp.	Rha	-	-	-	-	-	-	-	-	-	-
Dicranata sp.	Dic	-	-	3	-	9	5	5	9	25	13
Eloeophila sp.	Elo	-	-	-	-	-	-	-	-	5	-
Scleroprocta sp.	Scl	-	-	-	-	-	-	-	-	-	-
Rhypholophus sp.	Rhy	-	-	1	1	-	-	-	-	-	-
Thaumaleidae	Tha	-	-	-	-	-	-	-	-	-	-
Henerodromiinae	Hen	-	-	-	-	-	-	-	-	-	-
Plecoptera											
Leuctra hippopus (Kempny)	LeuH	-	-	-	-	-	-	-	-	-	-
Capnia spp.	Cap	-	-	-	-	-	-	-	-	-	-
Diura bicaudata (Linnaeus)	DiBi	-	-	-	-	-	-	-	-	-	-
Arcynopteryx compacta (McLachlan)	ArcC	-	-	-	-	-	-	-	-	-	-
Isoperla difformis (Klapálek)	IsDi	-	-	-	-	-	-	-	-	-	-
Taeniopteryx nebulosa (Linnaeus)	TaNe	-	-	-	-	-	-	-	-	-	-
Brachyptera risi (Morton)	BrRi	-	-	-	-	-	-	-	-	-	-
Amphinemura sulcicollis (Stephens)	AmSu	-	-	-	-	-	-	-	-	-	-
Protonemura meyeri (Pictet)	PrMe	-	-	-	-	-	-	-	-	-	-
Ephemeroptera											
Baetis buceratus (Eaton)	BeBc	-	-	-	-	-	-	-	1	-	-
Baetis bundyae (Lehmkuhl)	BeBn	-	-	-	-	-	-	-	-	-	1
Baetis vernus var.	BeVe	-	-	-	-	-	-	-	-	-	2
Baetis rhodani (Pictet)	BaRh	-	-	-	-	-	-	-	-	-	-
Acentrella lapponica (Bengtsson)	AcLa	-	-	-	-	-	-	-	4	-	21
Ephemerella aurivillii (Bengtsson)	EpAu	-	-	-	-	-	-	-	-	-	-

Appendix C

Ephemerella ignata (Poda)	EpIg	-	-	-	-	-	-	-	-	-	-
Paraleptophlebia submarginata (Stephens)	PaSu	-	-	-	-	-	-	-	-	-	-
Ameletus inapinatus (Eaton)	AmIn	-	-	-	-	-	-	-	-	-	-
Ameletus alpinus (Bengtsson)		-	-	-	-	-	-	-	-	-	-
Heptagenia sulphurea (Müller)	HeSi	-	-	-	-	-	-	-	-	-	-
Heptagenia flava (Rostock)	HeFl	-	-	-	-	-	-	-	-	-	-
Trichoptera											
Rhyacophila nubila (Zetterstedt)	RhNu	-	-	-	-	-	-	-	-	-	-
Plectronemia conspersa (Curtis)	PlCo	-	-	-	-	-	-	-	-	-	-
Neureclipsis bimaculata (Linnaeus)	NeBi	-	-	-	-	-	-	-	-	-	-
Psychomyiidae	Psyc	-	-	-	-	-	-	-	-	-	-
Potamophylax spp.	Pota	-	-	-	-	**18**	**6**	**4**	**19**	**20**	**2**
Coleoptera											
Helophorus sp.	Helo	-	-	-	-	-	-	-	-	-	-
Ilybius sp.	Illy	-	-	-	-	**1**	-	**1**	-	-	**6**
Agabus sp.	Aga	-	-	-	-	-	-	-	-	-	-
Hydroporinae	Hypo	-	-	-	-	-	**3**	-	-	**5**	**1**
Dytiscidae sp. A	ColA	-	-	-	-	-	-	-	-	-	**3**
Hydraena sp.	Hydr	-	-	-	-	-	-	-	-	-	-
Dryops sp.	Drps	-	-	-	-	-	-	**1**	-	-	-
Elmidae	Elmi	-	-	-	-	-	-	-	-	-	-
Coleoptera sp. B	ColB	-	-	-	-	-	-	-	-	-	-
Ostracoda	Ostr.	-	-	-	-	**23**	-	-	-	-	**3**
Hydracarina	Hyca.	-	-	-	-	**2**	-	-	-	-	-
Turbellaria	Turb.	-	-	-	-	**2**	-	-	**1**	-	-
Gastropoda	Gast.	-	-	-	-	-	-	-	-	-	-
Collembola	Coll.	**1**	-	**2**	-	-	-	-	**2**	-	**2**